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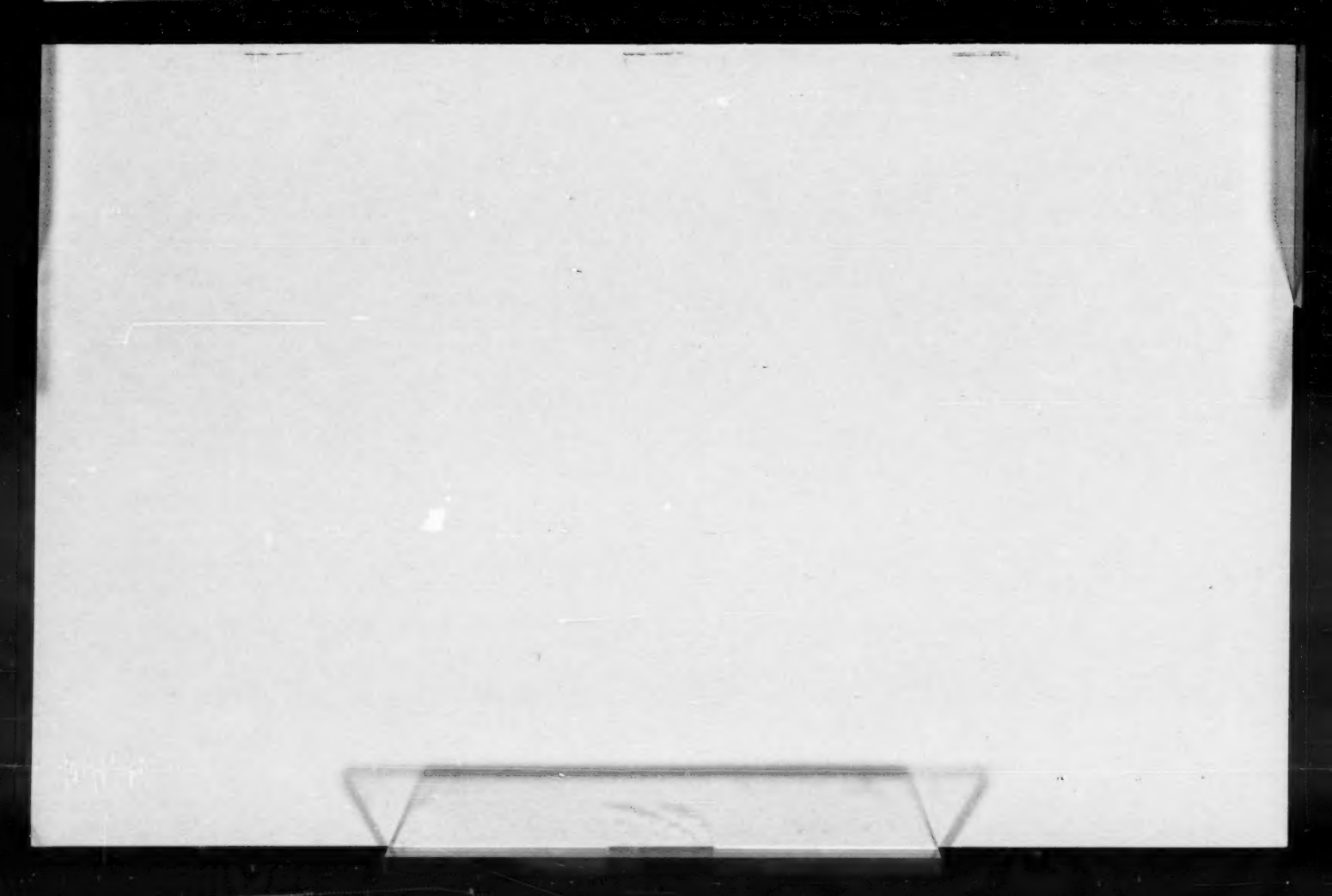

American Journal of Science

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FABRIC CHANGES IN YULE MARBLE AFTER DEFORMATION IN COMPRESSION

ELEANORA BLISS KNOPF

PART 1

ABSTRACT. Experimental deformation of a monomineral aggregate that is either statistically isotropic or statistically simple in fabric, carried out under controlled pressure-temperature conditions should give information on the process of deformation, provided that the fabric is studied before and after deformation by petrofabric analysis.

Yule calcite marble from Colorado has a relatively simple pattern of preferred orientation both dimensional and crystallographic and was therefore used by David T. Griggs for deformation in compression under confining pressures of about 10,000 atmospheres, at 20°C and 150°C, both dry and in the presence of carbonated water vapor. Petrofabric analysis proved that the deformation was essentially homogeneous.

In the undeformed marble, calcite was arranged in a distinct planar structure (s) = (ab) oriented parallel to the north-south vertical plane. Petrofabric study shows that this planar structure is determined by triaxial ellipsoidal grains of calcite oriented with the shortest axis of the ellipsoid normal to s, which is the "grain" of the quarry structure. The optic axes of the calcite grains tend to lie nearly normal to s but make an angle of about 26° with the pole of s, which is the east-west direction in nature.

Deformation was produced in three sets of cylinders, oriented so that the cylinder axis in one set was normal to s; in the other two sets, parallel to s but mutually perpendicular. In dry deformation at 20°C the maximum strength was in cylinders whose axis was normal to s. The stress-plan in these cylinders is unfavorable for twin-gliding because the orientation pattern of the undeformed marble would throw the direction sense in twin-gliding against the applied force in compression thus precluding movement by twinning. The preferred orientation of the calcite lattice would allow translation-gliding to operate in these cylinders in conformity with the Law of Maximum Resolved Shearing Stress. Deformation is an axial strain and the cross section of the deformed cylinder is circular. In a cylinder whose axis was parallel to s the strain was orthorhombic and the cross section after deformation was elliptical with the major axis of the ellipse always normal to s. This orientation would be expected from the original preferred orientation of the calcite in the undeformed fabric.

In dry deformation where the cylinder axes are parallel to s, the fabric of the undeformed marble is drastically rearranged into a new planar structure (s) = (a_2b_2) that is normal to the compressive force, and the optic axes of the calcite grains have assumed a new position nearly paral-

lel to the compressive force. The glide lamellae are close set and in many places bent and twisted. Many grains are cloudy and turbid, so that the microscopic texture shows no notable evidence of recrystallization even when the deformation was carried on at 150°C.

In deformation at 150°C in the presence of carbonated water, the fabric is entirely different. The grains are clear, lamellae are sharp and straight. The texture is clearly that of a recrystallized fabric. Unfortunately, reliable conclusions about fabric reorganization cannot be drawn from the single thin section that was cut from this cylinder, because of doubt as to the orientation of the section.

The present study of deformed Yule marble indicates the operation of intragranular gliding in conformity with the Law of Maximum Resolved Shearing Stress and suggests intragranular movement on two sets of intersecting glide planes. Conclusive proof of this mechanism, of the relative influence of twin-gliding and of translation-gliding, and of the crystallographic nature of operative glide systems will require further experimental work accompanied by detailed measurements of calcite axes and lamellae, grain by grain, in sections that are thinner than those used in the present study.

The present study has established that a radical change in preferred orientation, both dimensional and crystallographic, is caused by the deforming movement and that this change is definitely related to and controlled by the fabric pattern of the undeformed marble.

INTRODUCTION AND ACKNOWLEDGMENTS

A SERIES of marble cylinders, whose internal fabric had been studied by petrofabric analysis, was deformed in compression by Mr. David T. Griggs in the Harvard Physics Laboratories in 1936. In this paper is recorded the result of petrofabric analysis of these cylinders both before and after deformation. Continuation of the program for rock deformation as originally planned was interrupted by World War II. In 1943[1] an advance report on the work completed before the war was given before the American Geophysical Union. The present paper describes the preliminary work in detail and outlines suggestions for further work. The manuscript has been read by Professor D. T. Griggs, who has very kindly furnished the data on the experimental deformation, and by Professor F. J. Turner of the University of California, to both of whom I tender sincere thanks, as well as to Professor Horace Winchell of Yale University, with whom I have discussed numerous problems. Dr. James F. Bell kindly furnished the diagrams showing fields that are susceptible and non-susceptible to twin-gliding and the photograph of calcite

[1] Knopf, Eleanora Bliss. Fabric changes induced by Experimental Deformation of Marble. Am. Geophysical Union Trans. Pt. I, 271-272, 1943.

deformed by translation-gliding. My warm thanks are due to Professor George W. Bain of Amherst College, consulting geologist for the Vermont Marble Co. for data on the physical characteristics of the Yule marble and to the officials of the Vermont Marble Company who kindly facilitated my visit to the Yule quarry in Colorado for the purpose of collecting test material. The cost of cutting oriented cylinders for the deformation tests was covered by a grant-in-aid from the National Research Council and the experimental work was supported by the Committee on Geophysical Research and the Society of Fellows of Harvard University. Part of the apparatus for deformation at high confining pressure was constructed under a grant-in-aid from the Penrose Research Fund of the Geological Society of America. It is a great pleasure to acknowledge the kind assistance of these four organizations.

SCOPE OF THE INVESTIGATION

It is well known to metallographers that after a polycrystalline metal has been rolled or drawn it acquires a "texture", which is characteristically different for different kinds and degrees of working. By texture the metallographer means a concentration of certain crystal planes and vectors in definite direction with reference to the plane of working.

Many years before the metallographer recognized metal "textures" the geologist had discovered that deformed rocks have a "preferred orientation", in other words, a statistical concentration of crystal elements or of dimensional vectors in a definite direction with reference to the megascopic structure of the rock. In 1930 Sander[2] published numerous petrofabric diagrams illustrating the preferred orientation of various minerals in rocks of various sorts. In this way he was able to show that certain distinctive patterns of preferred orientation characterize rocks of different types. In the succeeding decade many other petrofabric diagrams have furnished a vast amount of data. The emphasis in all this work was laid upon the *kinematics* of the deforming process, which could be recognized by petrofabric analysis. As noted by Durand, writing in 1928 with the keen perception characteristic of so many French petrographers, "the dynamics is a

[2] Sander, Bruno. Gefügekunde der Gesteine. J. Springer. Wien, 1930.

much more delicate matter", which cannot be established conclusively by *this* method of studying deformed rocks.

The mechanism of the orienting process in rock minerals has been largely a matter of inference, because the data hitherto obtained by petrofabric analysis represent the end result of the process, and up to 1936 only two attempts had been made to relate preferred orientation in rock minerals to experimentally induced deformation; and in both of these experiments the applied force produced ruptural and not plastic[3] deformation.[4] In metal working, on the other hand, the process has always been a matter of observation, because the resultant texture is actually produced under controlled conditions.

In this way it has been established that the change in shape in deformed metal is accomplished by intragranular slip, the movement starting in those glide planes[5] on which the resolved shear stress in the glide direction is a maximum. As slip proceeds, the initially operative glide planes change position with reference to the direction of applied force and in doing so bring other glide planes, originally less favorably situated, into a position where they can operate to carry on the deformation. Intergranular movement is probably of subordinate importance in developing a preferred orientation in polycrystalline metal fabrics. The ability to deform by translation-gliding is more quickly attained in those metal crystal lattices that have several possible translation systems, such as in the cubic lattice of aluminum, than it is in the hexagonal lattice where the possibility of movement is restricted to one crystal lattice plane as in zinc. In zinc the ability to twin on a different lattice plane from the translation plane facilitates deformation.

Petrofabric analyis of deformed rocks (tectonites) had indicated the probable influence of the same mechanism of intragranular slip in rock deformation previously recognized

[3] Plastic is used here to characterize deformation exceeding the elastic limit in which the spatial continuity of the material is unimpaired.

[4] Sander, B., Felkel, E., and Drescher, F. K. Festigkeit und Gefügeregel am Beispiele eines Marmors. Neues Jb., BB59A, 1-26, 1929.

Bell, J. F. Festigkeit und Gefügeregel am Beispiel eines Granits. Neues Jb. BB71A, 193-213, 1936.

[5] "Gliding" comprises displacement by translation and by twinning. Slip and gliding are used here synonymously.

in metal deformation. In addition to the slip mechanism, it had also suggested the influence of grain rupture, followed by a dimensional rearrangement of particles into a preferred orientation governed by grain shape. When recrystallization increases the grain size, the preferred orientation of these seed particles is retained.

In 1934 it occurred to the author that the experiments on rock deformation under high confining pressure that were being conducted by Mr. David T. Griggs at Harvard University would furnish an ideal field for petrofabric investigation of experimentally deformed rocks. These experiments were being carried out under accurately controlled pressure-temperature conditions and therefore should give definite information on the nature of the orienting process, provided that the fabric of the rock is studied both before and after deformation.

An ideal rock fabric to be tested, under a given stress set-up, should be a statistically isotropic, homogeneous, monomineral aggregate, of grain size sufficiently large to be readily studied with the universal stage in measuring the orientation of the individual grains, and not so large but that in one thin section enough grains can be measured to give statistically a true sample of the whole.

In such an ideal rock fabric the mineral grains have a random orientation (a statistical scattering of position), for as soon as the individual grains show a definite alinement, either dimensional or crystallographic, the fabric is anisotropic.

SELECTION OF MATERIAL FOR STUDY

As Griggs had run a number of successful experiments on the deformation of limestone and marble at high confining pressure,[6] a calcite rock seemed a desirable monomineral aggregate to use in fabric studies. Experimental study of single calcite crystals had proved that the mechanism of deformation is by mechanical twinning and had suggested the concomitant influence of translation-gliding. The gliding planes are three rhombohedral planes; therefore considerable flexibility of deformation is expectable. It soon became

[6] Griggs, David T. Deformation of rocks under high confining pressures. Jour. Geology, **44**, 541-577, 1936.

apparent that in order to obtain the necessary grain size the material chosen would have to be a metamorphic marble (a calcite tectonite),[7] because homogeneous calcite marbles of depositional original could not be found.

It appeared possible that calcite grains in a limestone that had been marmarized by contact-metamorphic action would prove by statistical study to be of random orientation, provided that the thermal action had not been accompanied by a penetrative movement that would cause a preferred orientation of the constituents. The marble from the Yule quarry in Colorado has been considered to be a thermally altered limestone of late Paleozoic (Mississippian) age[8,9] and, unlike many contact-metamorphosed marbles it lacks contact silicate minerals. Therefore, in 1934 the author visited the quarry of the Vermont Marble Company from which came the block of "Golden Yule" marble used in the tomb of the Unknown Soldier in the National Cemetery at Arlington, Virginia. This quarry is on the west side of Yule Creek, three miles south of Marble, Gunnison County, Colorado.

The marble at the base of the quarry about 200 feet below the surface entrance appeared to be ideally suited for the purpose, so far as field observation could indicate. It is a uniform and approximately even-grained white marble and the only megascopic structure evident in the quarry is a set of fractures or joints running N65°E and dipping about 80°NW. Another set of discontinuous joints striking N55°W and dipping about 70°SW form *en échelon* zones not easily seen. The absence of bedding planes makes it possible to saw the marble into exceptionally large blocks. However, in spite of the massive character, the quarrymen recognize a certain anisotropy in the rock and they report that the "grain" of the

[7] A tectonite is a rock in which deformation has been accomplished by interrelated movements of individual fabric elements in such a way that the individual movements can be integrated into the movement as a whole. In a non-tectonite individual movements of components are independent and unrelated. Therefore, they imply nothing about movements of other components.

[8] Vanderwilt, J. W., and Fuller, H. C. Correlation of Colorado Yule marble and other early Paleozoic formations on Yule Creek, Gunnison County, Colorado. Colo. Soc. Proc., 13, 7, 439-464, 1935.

[9] Vanderwilt, J. W. Geology and Mineral Deposits of the Snowmass Mountain area, Gunnison County, Colorado. U. S. Geol. Survey Bull. 884, 19-21, 1937.

marble,[10] which is the plane of easiest splitting, strikes approximately north and dips westward at almost 90°. (See pl. 1).

A specimen of marble, measuring more than one cubic foot, was collected from near the quarry floor and the geographic orientation was marked on the block together with the direction of the grain.

In the laboratory a thin-section block was sawed from this large specimen with the orientation indicated in figure 1, a.

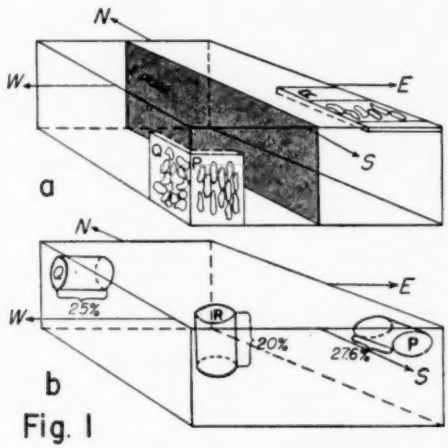


Figure 1. Orientation of thin sections and test cylinders of Yule marble before deformation in compression.

a) Thin section block with 3 mutually perpendicular sections P.Q.R. Megascopic *s* plane is determined by dimensional orientation of discoid grains.

b) Orientation of test cylinders. Numbers indicate percentage reduction of original cylinder after deformation. Dimensions of original cylinder, 1 inch x ½ inch.

The faces were lettered as follows:

1. P, vertical surface; normal to strike and normal to the dip of the grain.
2. R, horizontal surface; parallel to strike and normal to dip of grain.
3. Q, vertical surface; parallel to strike and dip of the grain.

[10] In marble quarrying "grain" is used as synonymous with "rift" in granite quarrying.

COMPOSITION OF THE YULE MARBLE

A small chip of the rock, about 2 cc. in volume, dissolved almost completely in cold dilute HCl within a few hours. A surface of about 3 cm. x 4 cm. was polished and stained with a molar solution of $Cu(NO_3)_2$ for less than three hours.[11] On fixation with NH_4OH the whole surface assumed a uniform blue color. These two tests indicate that dolomite is absent and that the Yule marble is practically a pure calcite marble.

The following analysis shows that the rock is made up almost entirely of calcite.

Chemical analyses of clear Yule Colorado Marble[12] *made under direction of G. W. Smith, Case School of Applied Science, Cleveland, Ohio, Oct.* 22, 1907.

$CaCO_3$	99.50
$MgCO_3$	.19
$FeCO_3$	.03
$MnCO_3$	.02
SiO_2	.05
Al_2O_3	.03
Fe_2O_3	trace
MnO_2	none
$CaSO_4$	.09
Undet	.09
	100.00

PHYSICAL CHARACTERISTICS OF THE YULE MARBLE

Bulk specific gravity is 2.70. True specific gravity is given by Griffiths[13] as 2.72. Porosity is low; about 0.15 per cent and elasticity is high. (Young's modulus is 4.01×10^5 kg/cm^2 when the force is applied parallel to the veining and 3.84×10^5 kg/cm^2 when the force is applied normal to the veining).[14] Griffiths[15] reports a porosity of 0.45 per cent and absorption of 0.19 on a specimen of Yule marble. When the

[11] Rodgers, John. Distinction between calcite and dolomite on polished surfaces. Am. Jour. Sci., 238, 797-798, 1940.

[12] Vanderwilt, J. W. Geology and Mineral Deposits of the Snowmass Mountain Area, Gunnison County, Colorado. U. S. Geol. Survey Bull. 884, 160, 1937.

[13] Griffiths, J. H. Physical properties of typical American rocks. Iowa Engineering Experiment Sta. Bull. 131, 12, 1937.

[14] Data furnished by courtesy of Dr. G. W. Bain, Consulting Geologist of Vermont Marble Co.

[15] Griffiths, J. H., loc. cit.

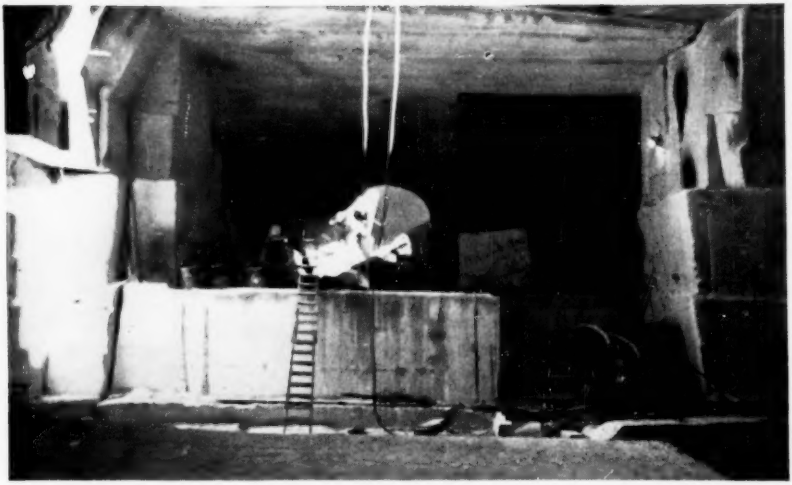


Plate 1. West wall at the floor of Yule Quarry, Colorado. Looking northwest. Shows method of sawing large blocks; dip of the "grain" in this face is steep towards the southwest (to the left). Courtesy G. W. Bain.

Plate 2. Thin section P, cut from the P face of the thin section block, x 10. Numbered grains represent traverses across the thin section.

Plate 3. Thin section R, cut from the R face of the thin section block, x 10.

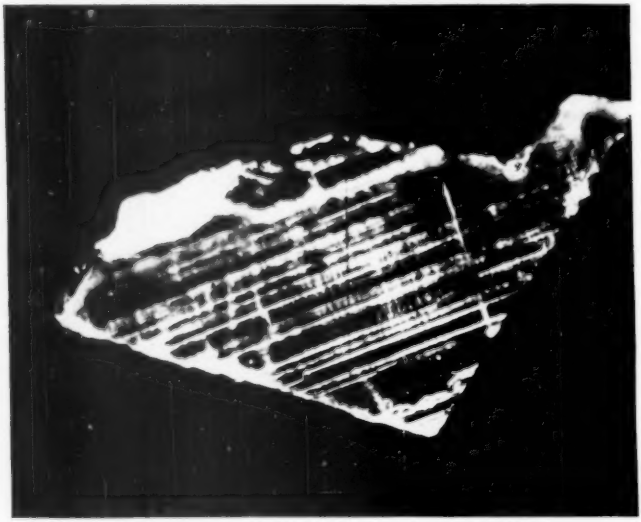


Plate 4. Translation-gliding striae in calcite crystal induced by a compressive force applied approximately parallel to the optic axis of the crystal. In this position twinning could not take place as the shearing stress on the $(01\bar{1}2)$ glide planes would be resolved in the wrong direction sense. Courtesy of J. F. Bell.

force is applied normal to the veining there is no hysteresis. On relief of force applied parallel to the veining, hysteresis amounts to 0.040 per cent. Permeability is moderately high (it requires 71 minutes for water to penetrate the stone to 1.5″). In one test run by Griggs and Bell on an R cylinder the crushing strength at room temperature parallel to the "grain" was 4220 psi = 296 kg/cm^2. Bain reports that in a direction normal to the "grain" the strength could be 8000 psi. In 1948 Professor Henry A. Lepper, Jr. of the Engi-

Linear Thermal Expansion of Yule Marble from 20°C. to Indicated Temperature, in Per Cent

(Rosenholtz, J. L., and Smith, D. T., Rensselaer Polytechnic Institute)

1 Orientation E-W	2 Orientation N-S	3 Orientation—vertical
∥ Maximum concentration of *c* axes of calcite.	⊥ Maximum concentration of *c* axes of calcite.	⊥ Maximum concentration of *c* axes of calcite.

First Heating

Temperature	Extension in %		
0°C.			
100	0.14	0.03	0.03
200	0.53	0.19	0.17
300	0.92	0.36	0.34
400	1.28	0.51	0.52
500	1.70	0.74	0.72
600	2.13	0.94	0.94
700	2.52	1.14	1.14
	Elongation 1.02%	Elongation 0.50%	Elongation 0.71%

Second Heating

Temperature	Extension in %		
0°C.			
100	0.05	−0.03	−0.021
200	0.16	−0.04	−0.033
300	0.31	−0.04	−0.027
400	0.42	−0.02	−0.005
500	0.62	+0.04	+0.06
600	0.96	+0.17	+0.20
700	1.25	+0.32	+0.37

neering School of Yale University tested strength to rupture in compression in two sets of oriented specimens of Yule marble.[16]

In the same year Professor Joseph L. Rosenholtz and Professor Dudley T. Smith of Rensselaer Polytechnic Institute determined the linear thermal expansion on Yule marble in three sets of oriented specimens. As this work is part of a recently begun, long-term program on determination of linear thermal expansion and transformation of crystallographically oriented minerals and rocks, Dr. Rosenholtz has very kindly released the data in the table (p. 441) for publication in the present paper.

The high values of the first heating cycle appear to be due to relief of some residual deformational strain, because the extension in each specimen at the end of the first heating-cooling cycle was a permanent elongation. On running the specimens through a second heating-cooling cycle, there was no further change in length at the end of the cycle.

PETROGRAPHIC FEATURES OF THE YULE MARBLE

The rock is a translucent, white, crystalline marble of medium grain. Careful inspection of both thin section and hand specimen shows that the calcite grains are distinctly elongate in the P and R face of the block, whereas in the Q face, which is cut parallel to the strike and dip of the "grain", they are practically equidimensional. In the P face the long dimension of the grains is parallel to the vertical axis in nature and in the R face the long dimension is in the north-south direction. (See fig. 1,a and pls. 2, 3.) Plates 2 and 3 are photomicrographs of thin sections P_2, and R_2 cut respectively from the P and R faces of the thin-section block. The orientation of these thin sections is shown in figure 1, a.

The average grain intercept is given in the following table:

	Average ratio between the longer and shorter grain intercepts measured in each section	Dimensions in Millimeters
P	1.8:1	9: .5
R	3:1	1.5: .5
Q	1:1	.5: .5

[16] Lepper, H. A., Jr. Compression tests on oriented specimens of Yule marble: Am. Jour. Sci., vol. 247, August 1949 (in press).

This indicates an arrangement of ellipsoidal calcite individuals occupying the plane of the "grain" in such a way that the short axes of the ellipsoids are normal to the "grain" of the marble. The calcite forms a granoblastic fabric whose components, in general, are of nearly the same size. The grains are clear, sharply transparent, and show numerous lamellae separated by lines that become thin and sharp when turned on the universal stage into the position where the planes of separation are parallel to the microscope tube. Some grains show only one set of parallel lines. Many grains show two or more intersecting sets of parallel lines. In some grains it is difficult to decide by inspection whether these lines are the traces of twin-gliding planes or of cleavage planes or of translation-gliding planes. The positions of all the lamellae sets in each grain were measured and recorded on the projection net by plotting the pole of that particular set of lamellae planes. The way in which lamellae due to twin-gliding, translation-gliding, and cleavage were distinguished is described later.

PART I.

Preliminary Petrofabric Analysis of Yule Marble (before experimental deformation)

From the thin sections cut parallel to the P, Q, and R faces of the thin-section block petrofabric analyses of the calcite fabric were made by measuring and projecting on to the lower hemisphere of a reference sphere the positions in space of the calcite axes and of the poles of the calcite lamellae. These positions are all recorded on an equiareal (surface-true) net.

Measurement of lamellae. In measuring the pole of a given set of parallel lamellae the grain is rotated upon the microscope stage (in other words around the vertical axis) until the traces of the lamellae are parallel to one of the cross hairs.[17] The grain is then tilted upon the N-S (A_2) or the

[17] The lamellae should be brought parallel to a cross hair in such a way that the vibration direction of the slow ray in the calcite is parallel to the vibration direction of the polarizer because then the index of refraction in the grain is the same as the index of refraction of the hemisphere. The hemispheres used in measuring calcite usually have an index of 1.649, which is ω in calcite. If the trace of the lamellae is placed so that the fast ray in the grain is parallel to the vibration direction in the lower nicol, the angular reading should be corrected for the difference in index between the grain and the hemisphere.

E-W (A_4) axis of the universal stage until the lines marking the intersections of the lamellae with the thin section are parallel to the microscope tube, in which position the lines show the maximum thinness and sharpness. However, lamellae that lie in or near to the plane of the thin section can never be turned up to a position parallel to the microscope tube owing to the fact that after the universal stage has been rotated for a certain angle (ϕ), about either the N-S (A_2) or E-W (A_4) axis, total reflection occurs. This angle (ϕ) depends upon various factors such as the relative indices of the hemispheres and of the mineral grain, the microscope constants, and so forth. In the present work total reflection occurs after a rotation of about 45°. This gives a circular "blind spot" or "unmeasurable area" on the projection net with a radius equivalent to a distance of 45° from the center of the net. Whenever two mutually perpendicular sections of the material are available, it is possible to fill this "blind spot", by utilizing a second section at right angles to the first to measure enough poles that the area common to both projections contains an equal number of poles. Then these poles from the second section occuring in the area that corresponds to the blind spot of the first section are themselves rotated to the position of the first section and thus the unmeasurable area is filled,[18] and a complete diagram is prepared.

The completeness with which the blind spot in any diagram can be filled depends upon the angle at which total reflection occurs—if the angle of total reflection (ϕ) is $> 45°$, the radius of the corresponding blind spot must be less than 45° and therefore the blind spot in one section must lie within the measurable area in the section at right angles to the first. If the radius of the blind spot is > 45 ($\phi < 45°$) a part of the blind spot of the first section will lie within the unmeasurable area of the second section and some poles will always be missed in both sections. As long as the radius of the blind spot is not greater than 50° any essential concentration that is missed in two sections that are mutually perpendicular, for example P and R, can be found in the third section, Q, normal to the other two.

[18] Knopf, E. B., and Ingerson, E. Structural Petrology. Geol. Soc. America Mem. 6, 230-233, 1938.

COMPLETE DIAGRAMS

As the contoured diagram represents relative density of measured poles, it is obvious that a petrofabric analysis can never represent the measured field correctly until the unmeasurable area is filled. Therefore, it is absolutely useless to draw final conclusions about significance of maxima, presence or absence of girdles, etc., until the diagram is completed. However, if the diagram shows a strong peripheral concentration of poles, it is advisable to contour the incomplete diagram in order to evaluate the maxima that are peculiar to the diagram that has been measured, some of which will not reappear in the measured area of other sections. For example, suppose we measure a fabric in which there is a strong concentration of lamellae poles around the emergence of the east-west axis causing a maximum around the east-west pole of a *horizontal* section. If we measure a diagram from a section *at right angles to the first and looking north* the maximum recorded in the first analysis will reappear in the second diagram. But suppose we measure a section *at right angles to the first and looking east or west* the maximum around east or west will never be found. Its absence in the third section is no evidence of inhomogeneity in fabric and similarly its presence in the third section when filled from either of the other two is no evidence of homogeneity because that maximum can never be recognized by measurement anywhere except in the sections that are parallel to the east-west axis.

Moreover the fact that we have in the center of the calcite lamellae diagrams a blind spot with a radius of about 45° means that in any one section there is outside this blind spot a peripheral area where the density is indeterminate because the relative density of concentration of the measured poles in the given section will be affected by the poles that lie in the unmeasurable area and thus do not show in the measured section. Within the periphery of the projection net there is a zone where the number of poles in the given counter circle is not changed by any poles that are outside of this zone. Likewise in the blind spot itself there are no poles within the counter zone. But in the transition zone between the peripheral zone of the projection net and the circumference of the blind spot, a counter will catch the poles that were actu-

ally measured in the measurable area but will also include a part of the unmeasurable area which cannot be included in the count until the blind spot is filled by rotation of poles from another section. When the diagram is completed a submaximum that showed up in counting the diagram measured may shift its place or even "wash out" completely. Therefore, while there is a certain value in contouring an unfilled diagram it should *never* be used for final conclusions without also contouring the completed diagram. What appears to be a good single peripheral girdle in one measured diagram may prove to be two or even three girdles when the diagram is completed, a difference that would have an important tectonic significance in a regional study.

SELECTIVE DIAGRAMS

In order to facilitate the study of selective "elemental diagrams", i.e., diagrams prepared by grouping the measured data from certain kinds of grains, selected with reference to grain size, presence or absence of lamellae, etc., the thin sections should be photographed and the grains in the photomicrograph should be numbered consecutively. Then each grain measured can be identified upon the photograph and measured data, lamellae poles or optic axes, edges between lamellae, etc., can be recorded against the appropriate number. Such a record makes it easy to construct diagrams from any desired grouping of grains.[19]

HOMOGENEITY OF THE FABRIC

If a statistical analysis of preferred orientation of grains in a given fabric is to be used to draw sound conclusions about the behavior of the fabric under the application of a deforming force, the field of matter under consideration must be statistically homogeneous. In other words, whatever may be the structure of the field under consideration, whether it is statistically isotropic or anisotropic, any two parts that are similarly oriented must be identical.[20]

[19] In early stages of the work the importance of correlated grain measurements was not appreciated, but all diagrams made later were prepared in this way.

[20] The importance of determining homogeneity in petrofabric analysis of a rock, which seems to have been overlooked recently by some workers, is so great that the procedure is described here in detail.

An easy way to test homogeneity in the *area* technically known as the "field" of a thin section is to measure the grains in separate traverses that cross the thin section in different parts. The poles that make up the different traverses are contoured separately in elemental diagrams and are compared to determine whether any essential difference in fabric is indicated. All the measured poles are then collected into one "collective diagram", which is contoured and compared with the "elemental diagrams" of the individual, separate traverses. In a fabric that is statistically homogeneous all these diagrams, both collective and elemental, will show essentially the same pattern.

A fabric may be essentially homogeneous in the field represented by the *area* of the thin section but may be distinctly inhomogeneous in the field represented by the *volume* of a thin-section block. The test for this is made by comparing diagrams cut from different faces of the block. For example, a diagram is prepared from a thin section cut from the P face. Then it is geometrically rotated to the position of the R section by shifting the contours 90° along small circles that are normal to the axis common to both faces, which in the P and R faces is the east-west geographic axis. This *rotated* diagram shows the pattern as it would appear in a diagram *measured* from R if the fabric is homogeneous. The diagram actually measured in R is then compared with the diagram that was measured in P and rotated to R. If the diagrams do not show a reasonable correspondence it indicates an inhomogeneity in the field under consideration and by this comparison it is possible to determine the direction of shift in the fabric pattern of P in a third dimension at right angles to the area of the P section.

SIGNIFICANCE OF PATTERN

In any statistical study the data on which conclusions are based must represent a true sample of the whole that is being studied. For example one bad egg in a box of twelve eggs does not mean that in a crate of twelve dozen eggs there will be a bad egg in each dozen because one box may have chanced to get the only bad egg that was present in the whole 144 eggs. But if each of six boxes has one or two bad eggs it is much more likely that the ratio of bad to good in the whole crate

will turn out to be 1:12 instead of 1:144. A great deal has been written about significance of maxima in petrofabric analysis and about the way to determine this significance mathematically. However, for purposes of fabric analysis the meaning of a given maximum depends actually upon its persistence and position within a given field of distribution. As it is impossible to evaluate homogeneity without making collective diagrams from numerous elemental diagrams, the easiest way to determine the significance of a given maximum is to watch it from one diagram to another during the course of the study. If the same maximum reappears in approximately the same place in a number of successive traverses in a thin section, or in a number of thin sections in a rock, the concentration of poles represented by the maximum is not fortuitous but is a significant indication of a preferred orientation that has a meaning in interpreting fabric. Moreover, if in several thin sections of a rock, the same relative arrangement of maxima recurs but in a notably different relation to the geographic coordinates, the shift in fabric pattern indicates a structurally significant shift in the fabric structure.

For that reason it is a good idea, when measuring several hundred grains to count first fifty, then one hundred, and so on in successive groups and to notice what parts of the pattern are constant from a count of a few poles up to a count of several hundred poles, also to notice which parts of the pattern disappear and which are intensified and perhaps shifted in successive counts.

The diagrams listed in the following table were measured and contoured by the author from calcite grains in the Yule marble. The orientation of the thin-sections from which the diagrams were measured is shown in figure 1, a.

To get an independent check on the diagrams from the P, R, and Q thin sections, measured by the author, 300 calcite lamellae in P_1, 100 in R_1, and 100 in Q_1, were measured and contoured by Dr. James Forbes Bell, who was at that time research assistant to the author. These diagrams checked in all essential particulars with the other diagrams from sections in the P, R, and Q faces.

In order to test the homogeneity of the whole thin-section block a second set of chips, labelled P_2, R_2, and Q_2, was cut from a different part of the thin-section block and the thin

Diagrams prepared from undeformed Yule marble.

From P face	From R face	From Q face
P_1 thin section	R_1 thin section	Q_1 thin section
Calcite lamellae		
90 poles (elemental)	48 poles (elemental)	190 poles
150 poles (elemental)	72 poles (elemental)	*100 poles*
305 poles (collective)	120 poles (collective)	375 poles (complete collective filled from P_1)
385 poles (complete collective filled from Q_1)	165 poles (collective for one traverse)	383 poles (complete collective filled from R_1)
355 poles (complete collective filled from R_1)	115 poles (from another traverse)	
150 poles[21]	328 poles (collective from both traverses)	
150 poles	398 poles (complete collective from both traverses filled from Q_1)	
300 poles (collective)	403 poles (complete collective filled from P_1)	
520 poles (collective)	*100 poles*	
Calcite optic axes		
40 axes (elemental)	20 axes (elemental)	
75 axes (elemental)	69 axes (elemental)	
210 axes (collective)	109 axes (collective)	
230 axes (collective)	255 axes (collective)	
P_2 thin section	R_2 thin section	
Calcite lamellae		
165 poles (in one traverse)	165 poles (in one traverse)	
165 poles (in another traverse)	166 poles (in another traverse)	
330 poles (collective)	331 poles (collective)	
410 poles (complete collective filled from R_2)	370 poles (complete collective filled from R_2)	
Calcite optic axes		
	38 axes	
282 axes collective from P_1 and P_2.		

sections P_2 and R_2, made from these chips, were measured for optic axes and lamellae in calcite. The elemental and collective diagrams from the P_1, R_1, and Q_1 faces respectively, and from the P_2 and R_2 faces respectively, checked well enough to

[21] Italics indicate diagrams measured by Dr. James Forbes Bell, at that time research assistant to the author.

indicate an essential homogeneity in the field of the thin section in both sets of thin sections. Moreover, the comparison of P_1 with P_2 and of R_1 with R_2 indicates that the fabric is essentially homogeneous within the field of the material from which the test cylinders were cut for deformation. For this reason no new Q diagrams were measured from the second set of thin sections.

PETROFABRIC ANALYSIS

OPTIC AXES

P diagrams. The analysis of the calcite optic axes diagrams shows a striking homogeneity of calcite fabric within the field of the thin section. A strong two-fold maximum Ax_1 and Ax_2 is clearly evident, striking about N65°W and separated upwards and downwards into two divisions. The north-south spread of this maximum is about 45°, the east-west spread about 30°. It only requires a count of 43 optic axes measured in the P_1 section (fig. 2) to indicate clearly the location of this two-fold maximum and the same maximum recurs in the count of 75 axes (fig. 3) and persists also in 210 axes all measured in P_1. This similarity in diagrams from all three counts shows the homogeneity of the field of the thin section. The diagram from 282 axes (fig. 4) measured in both P_1 and P_2 is practically identical with that from 210 axes measured in P_1, thus indicating that the fabric is homogeneous within the field of the thin section block. A submaximum (Ax_3) on the periphery of the diagrams, near the east-west pole, has begun to appear in the diagram of 75 axes and is definitely established in the collective diagram of 282 axes. The pattern in figure 4 is sharp,—a main maximum representing axes striking about N65°W with a tendency to swing upward and downward and a submaximum representing axes that lie horizontally in an east-west direction.

R diagrams. The optic axes from the R_1 section were measured with the same precautions to observe the homogeneity within the field of the thin section as in measuring optic axes from P_1 section. 122 optic axes measured from the R_2 section (fig. 5) showed such a good coincidence with 110 optic axes measured from R_1 (fig. 6) that a diagram was contoured from 242 axes measured in R_1 and R_2 (fig. 7). This represents the R field of the thin section block. In order to test

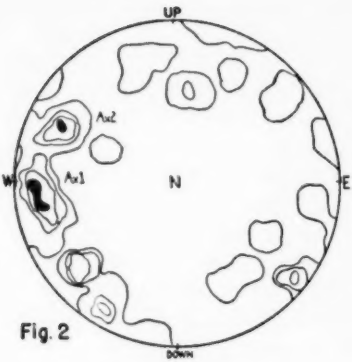


Fig. 2

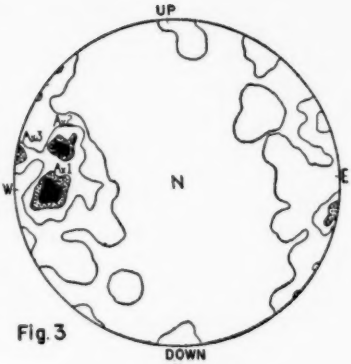


Fig. 3

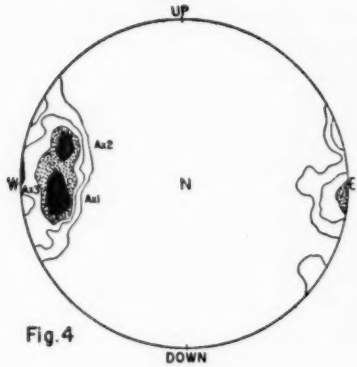


Fig. 4

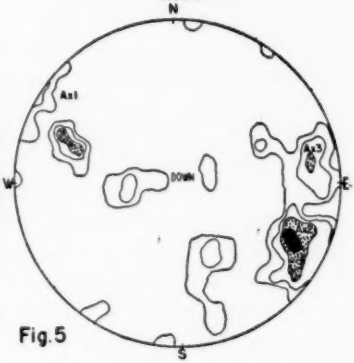


Fig. 5

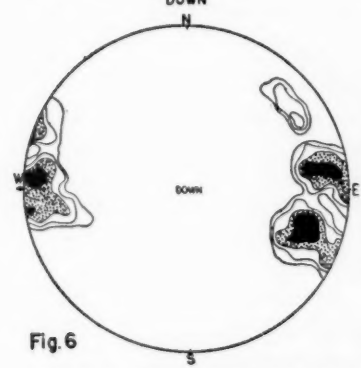


Fig. 6

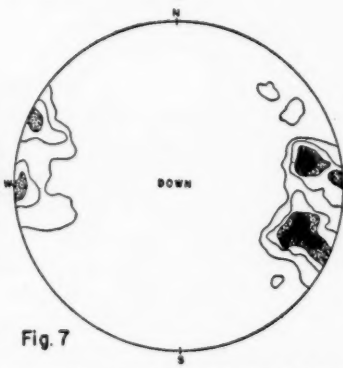


Fig. 7

Figure 2. 43 optic axes of calcite in P_1 section. Contours (10-9)-8-5-3-0%.
Figure 3. 75 optic axes of calcite in P_1 section. Contours (12-9)-7-4-2-0%.
Figure 4. 282 optic axes of calcite from P_1 and P_2 sections. Contours (8-6)-4-3-2-0%.
Figure 5. 122 optic axes of calcite in R_2 section. Contours $>$ 6-4-3-2-0%.
Figure 6. 110 optic axes of calcite iln R_1 section. Contours (8-6)-4-3-2-0%.
Figure 7. 242 optic axes of calcite from R_1 and R_2 sections. Contours (8-6)-4-3-2-0%.

the homogeneity of the fabric in the field between P and R, this diagram of axes in R was checked against a diagram made by rotating the diagram of 282 axes measured in P_1 and P_2 to the position of R (fig. 8). The high degree of coincidence between these two confirms the conclusion that the fabric is essentially homogeneous within the field from which the test cylinders were cut for experimental deformation. The essential feature of the fabric is the concentration of axes into an approximately horizontal position striking about N65°W.

Q diagrams. No calcite axis diagram was made from Q thin section because this section is approximately normal to the concentration of optic axes. Therefore, the optic axes must be measured by setting them in the axis of the microscope tube, which is difficult to do with great exactitude in a section normal to the optic axis because it is impossible to determine the position of total darkness within a range of several degrees. In a mineral with the high birefringence of calcite, it is particularly difficult to determine the exact position of total extinction. Many grains in this section show a small and variable but distinct biaxiality. Therefore, as the essential homogeneity of the fabric has been established by rotating the lamellae and axes diagrams from P to R, it was decided the position of the axes in Q could be shown by rotating the axes measured in P_1 or R_1 to the position of Q as accurately as by actual measurement in Q (fig. 9).

LAMELLAE

P_1 and P_2 diagrams (unfilled collective). The diagram of 305 calcite lamellae from the P_1 face looking north (fig. 10) shows a clear segregation of poles into two 100° peripheral arcs extending about equal distances on either side of the east-west pole of the diagram. The vertical axis in Nature emerges in well-defined minima on the periphery of the projection net at 90° from the east-west pole. The same arcuate concentration of lamellae around the periphery reappears consistently in all the collective diagrams.

The collective diagram of 300 lamellae made by Dr. James F. Bell, shows a good correspondence with figure 10, which is the collective diagram of 305 lamellae measured by the writer.

Figures 11 and 12 are two elemental diagrams made from two traverses of 165 lamellae each, in the thin section P_2 which

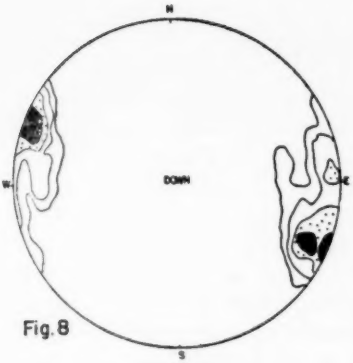


Fig. 8

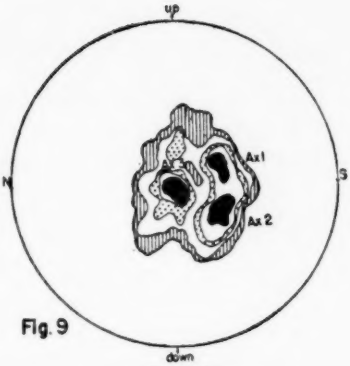


Fig. 9

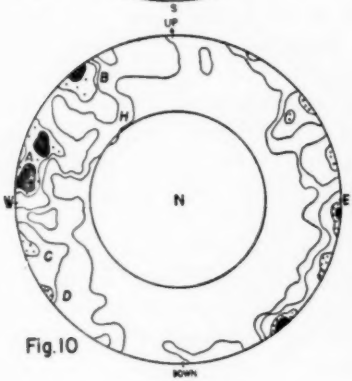


Fig. 10

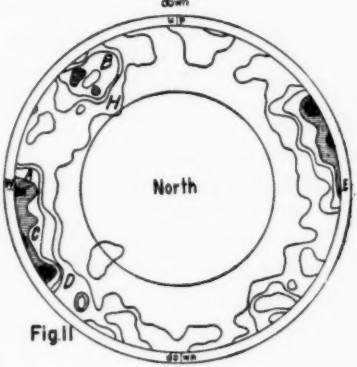
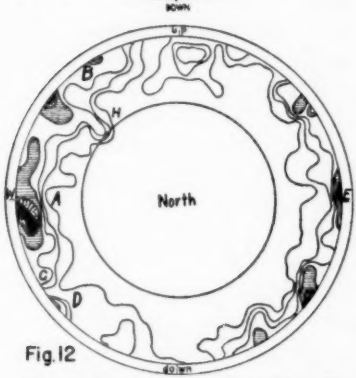


Fig. 11



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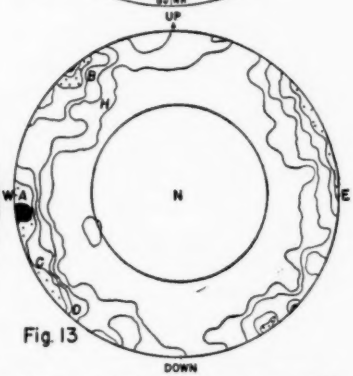


Fig. 13

Figure 8. 282 optic axes from P_1 and P_2 rotated to the position of R.

Figure 9. 160 optic axes of calcite measured in P and 160 measured in R rotated to the position of Q. Contours (7-6)-5-4-3-2-0%.

Figure 10. 305 poles of calcite lamellae in P_1 section. Contours (5-4)-3-2-1-0%.

Figure 11. 165 poles of calcite lamellae in P_2 section. First traverse. Contours (6-5)-4-3-2-1-0%.

Figure 12. 165 poles of calcite lamellae in P_2 section. Second traverse. Contours (7-6)-5-4-3-2-1-0%.

Figure 13. Collective diagram of 330 poles of calcite lamellae from P_2 section. Contours (6-5)-4-3-2-1-0%.

was cut from a different part of the thin section block. A collective diagram of 330 lamellae in figure 13 was made by combining these two elemental diagrams from P_2. These P_2 diagrams are all essentially homogeneous with each other and with the P_1 diagrams. The peripheral maximum belt extends a little farther upwards from the emergence of the west pole in diagrams from P_1 than it does in diagrams from P_2 thus indicating that there is a slight undulation around the north-south axis in the vertical north-south plane, a conclusion that is supported by the comparison of the P and R diagrams.

The two collective diagrams made from 330 and from 305 lamellae show, within the occupied 100° arc, and within the measurable field in P, a definite concentration of poles into one dominant maximum A close to the east-west pole. Another distinct submaximum B is about 45° above A. On the periphery of the diagram there are two submaxima C and D. The fact that these maxima persist in approximately the same place and approximately the same shape when the count is stepped up from 150 to 500 poles indicates that they represent significant rather than accidental concentrations of lamellae. This conclusion is further confirmed by the fact that even in as low a count as 90 poles, the general position of A and B is outlined by an area of relatively high concentration. The detailed pattern of A, and the submaxima C and D appear when more poles are counted.

The upper left hand quadrant in all the diagrams of P, i.e., the upper north-west quadrant indicates a northward pull of the arcuate area of high concentration. This is shown by the recurrence of a sub-maximum H of varying intensity inside the peripheral zone of the diagram. However, the fact that H does lie *inside* the periphery and within the transition zone of incomplete counting makes it impossible to draw correct analytical conclusions from the position of H until the diagram is filled. The only conclusion that can be safely drawn from the unfilled diagram of P is that in the field of the thin section and of the thin section block, the fabric is essentially homogeneous and that there are two significant maxima and one or two submaxima restricted to a peripheral arc passing through the east-west pole and extended upward and downward on both sides of this pole.

R_1 and R_2 diagrams (unfilled collective). Elemental and

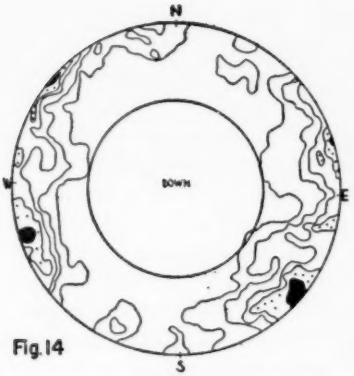


Fig.14

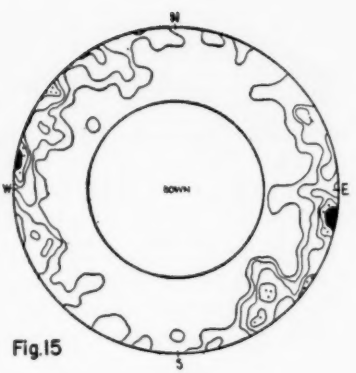
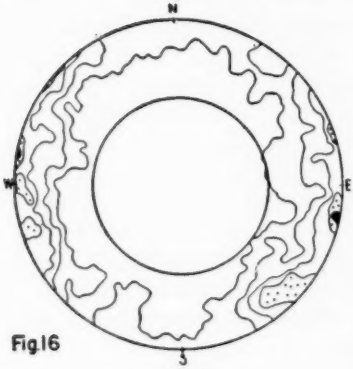


Fig.15



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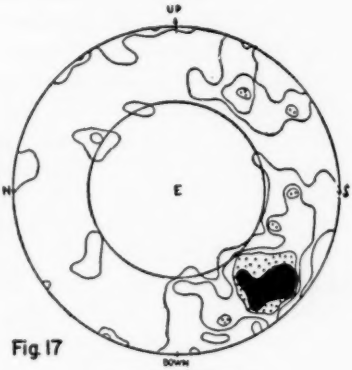

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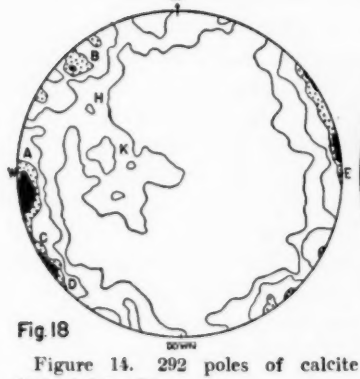

Fig.18

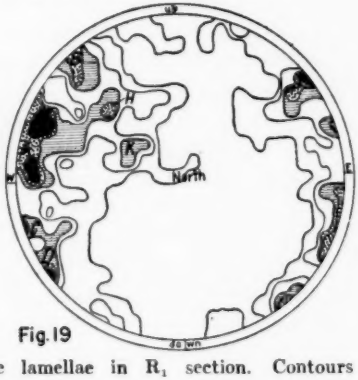

Fig.19

Figure 14. 292 poles of calcite lamellae in R_1 section. Contours (6-5)-4-3-2-1-0%.

Figure 15. Collective diagram of 203 poles of calcite lamellae in R_2 section. Contours (7-5)-4-3-2-1-0%.

Figure 16. 494 poles of calcite lamellae in R_1 and R_2 sections. Contours (6-5)-4-3-2-1-0%.

Figure 17. 190 poles of calcite lamellae in Q section. Contours (6-5)-4-3-2-1%.

Figure 18. 410 poles of calcite lamellae in P_2, 325 poles measured in P_2, 85 poles rotated from R_2 to fill P_2. Contours (6-5)-4-3-2-0%.

Figure 19. 385 poles of calite lamellae in P_1 filled by rotation of 80 poles from Q. Contours (5-3.5)-3-2.5-2-1-0%.

collective diagrams from the R_1 section, cut from the horizontal plane and mounted so that looking down in the thin section is looking down in Nature, show, near the emergence of the east-west axis, the same concentration of poles that characterized the diagrams from P_1. There is also a northward and southward extension of the peripheral zone of high concentration forming an arc of 80°-90° on both sides of the east-west axis, that shows plainly in the diagram of 292 calcite lamellae from R_1 (fig. 14). A minimum near the north and south poles in the R diagram could never appear in the diagram measured from P because the area around the north and south pole is unmeasurable in P. The same minimum shows clearly in the diagram measured by Dr. Bell from Q, (fig. 17). The general pattern of the calcite lamellae, deduced from the two diagrams from P and from R, is a concentration common to both diagrams, covering a polar cap of the projection sphere of about 30° radius. The A maximum in P reappears in R. The B and D of P fall outside of the measurable area in R and therefore do not appear in the R diagram.

The diagram from the thin section R_2 was contoured first in two elemental diagrams from two traverses in different parts of the thin section. The field of the thin section proved to be reasonably homogeneous. Therefore, all the poles measured in R_2 were contoured in a collective diagram of 203 lamellae (fig. 15). This collective diagram of 203 lamellae in R_2 coincides so well with the collective diagram of 292 lamellae in R_1 that a collective diagram of 494 lamellae from R_1 and R_2 (fig. 16) represents the field of the whole thin section block in the horizontal plane. The same pull from the periphery toward the vertical axis that showed in the quadrant delimited by the north, west and vertical axis in the diagram of P_1 at H reappears in the diagram of R_1 in the corresponding quadrant delimited by the south, east and vertical axis. But, as in the diagram from P_1, so in the R_1 diagram it is impossible to evaluate the significance of this area of high concentration because the true relative concentration can only be found from analysis of the Q_1 section.

Q_1 diagrams (unfilled collective). Two diagrams of 100 and 190 poles of calcite lamellae each made from the Q_1 section looking east (fig. 1,a) coincide so closely that the field of the thin section can be considered homogeneous. Figure 17,

which is a diagram of 190 lamellae shows a strong concentration in the lower southeast quadrant. This maximum seen in diagrams from Q is clearly indicated at H in the diagrams from P and from R although it can only appear in its entirety in the diagram from Q. There is also a submaximum beginning to appear in the upper southeast quadrant in the 190 pole diagram. But more than one half of the field of the projection is unoccupied in Q, which is what is to be expected on account of the strong concentration at A around the emergence of the east-west axis in the P and R diagrams, a concentration that could never appear in Q diagrams. Therefore, the measured maximum is over-emphasized in Q because of the absence of the maxima that are so prominent in the diagrams from P and R. For this reason the diagram measured from Q is of comparatively little value in interpreting the preferred orientation until Q is filled, both from P and from R.

FILLED DIAGRAMS

The three diagrams from the P, R and Q sections were filled respectively from sections parallel to the two faces at right angles to P, R, and Q, in order to check more closely the slight inhomogeneity in the field of the thin section block that is shown by the unfilled diagrams. Lamellae diagrams from P filled from R and Q are shown in figure 18 and figure 19. The correspondence between the P diagrams filled from R and from Q is good although the lamellae maximum at the west pole of the diagram is above the west pole in P_1 and below the west pole in P_2, a fact that is explicable by the oscillation of the axes maximum on either side of the east-west pole. A complete collective diagram was then made from 756 poles from P_1 and P_2, filled from R_1 and R_2 (fig. 20) for comparison with 656 poles from R_1 and R_2 filled from P_1 and P_2 (fig. 21). Figure 22, which is a lamellae diagram measured in Q and filled by poles rotated both from P and from R shows that the dominance of the east-west maxima has relegated the maximum of the unfilled Q diagram to a submaximum.

Then 385 lamellae poles from P filled from Q (fig. 19) were rotated to the position of R (fig. 23) for comparison with figure 21 (656 poles from R_1 and R_2 filled from P_1 and P_2). The correspondence between these lamellae diagrams in the areas common to both P and R is good. The correspondence between

the axis diagram measured in P and rotated to R (fig. 8) and the diagram measured in R (fig. 7) is also good and the essential homogeneity of the fabric is established.

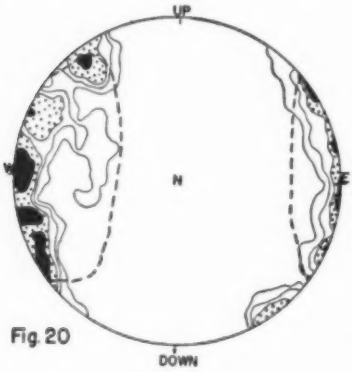

Fig. 20

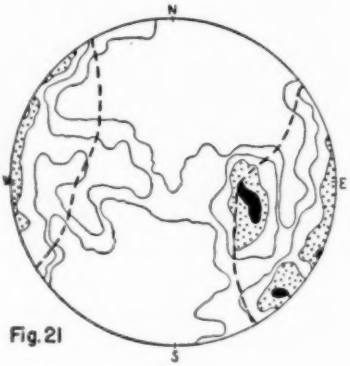

Fig. 21

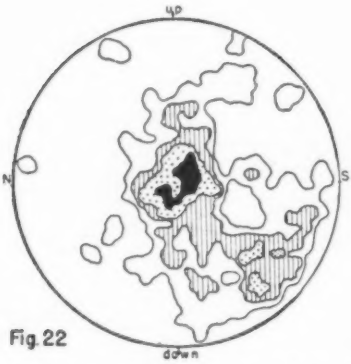

Fig. 22

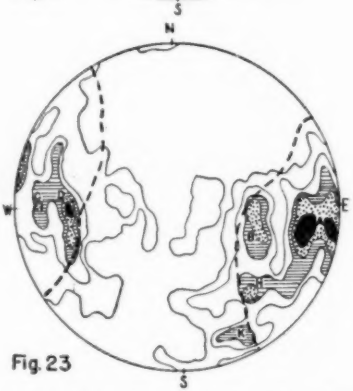

Fig. 23

Figure 20. 756 poles of calcite lamellae: 305 poles from P_1, 315 poles from P_2, filled with 52 poles from R_1 and 84 poles from R_2. Contours (5-4)-3-2-1-0%.

Figure 21. 656 poles of calcite lamellae from R_1 and R_2 filled from P_1 and P_2. Contours (5-4)-3-2-1-0%.

Figure 22. 338 poles of calcite lamellae in Q section: 172 measured in Q, 87 rotated from P, 78 rotated from R. Contours (6-4)-3-2-1-0%.

Figure 23. 385 poles of calcite lamellae in P_1 filled from Q and rotated to the position of R. Contours (5-3.5)-3-2.5-2-1-0%.

INTERPRETATION OF THE LAMELLAE DIAGRAMS

Both P and R diagrams indicate a scattering of maxima within the respective fields of *high concentration* (Überbesetzung), i.e. a certain multiplicity of maxima. Scattering of maxima in lamellae diagrams may mean one of two things:

(1) an external rotation of the fabric has involved a flexure, which entails a relative displacement of the mass as a whole. If calcite lamellae or cleavage planes of mica are arranged parellel to the *s* plane in a flexural slip fold, the poles within the field of that flexure will occupy positions that are definitely oriented with respect to the orientation of the whole mass but which are different in sections cut from different positions within the flexure.[22] The resultant fabric will be inhomogeneous and as the fabric of the Yule marble is essentially homogeneous the various maxima in the lamellae diagrams do not indicate flexural slip in the fabric. (2) An internal rotation has resulted in the formation of two or more interesting *s* planes along which the fabric elements are alined. The resultant fabric will be homogeneous.

Calcite lamellae can result from the polysynthetic development of mechanical twinning along planes of displacement that are parallel to $(01\bar{1}2)$. This method of twin-gliding can be produced in the laboratory by the so-called Baumhauer experiment. Bell[23] has also induced translation-gliding in calcite by applying a force in such a way as to inhibit movement in the sense of the twin-glide direction in $(01\bar{1}2)$. Therefore in his experiment the lattice could not deform by twin-gliding but the calcite did deform by translation-gliding in a homogeneous strain with the development of lamellae parallel to $(01\bar{1}2)$ in a manner analogous to the production of slip bands in metal working. See Plate IV.

Sharp lines representing traces of surfaces of discontinuity in the grains can also be the traces of rhombohedral planes parallel $(0\bar{1}11)$. Therefore, it is important to know the crystallographic relation of given maxima to the optic axes maxima. This relation can be determined by measuring the optic axis in each grain together with the trace of all the lamellae in this grain. Considerable drawback to exact measurement of both elements in the same grain is the fact that relatively thick sections give the most satisfactory results in placing the trace of lamellae in the vertical position, whereas relatively thick sections are eminently unsatisfactory for the accurate placing of optic axes in a measurable position in a mineral of such high birefringence as calcite. Unfortunately,

[22] Knopf, E. B., and Ingerson, E. Structural Petrology. Geol. Soc. America. Mem. 6, 77-79, 1937.

[23] Bell, James F. Personal Communication.

in the first work on the undeformed fabric the axes and lamellae were measured separately, so they cannot be directly related, grain by grain. However, in later work grain measurements were recorded grain by grain. Then the locus of *e* planes {0112} that could belong to the axes occupying the maximum in the axis diagram was plotted. The lines marking the outer limit of possible *e* planes related to the axes maximum are shown by the heavy dashed line in figures 20, 21 and 23. They coincide so well with the outer limits of the lamellae maxima that probably most of the measured lamellae represent *e* planes. This is confirmed by the evidence of those grains in which axes and lamellae were measured grain by grain.

GENERAL CONCLUSIONS IN REGARD TO THE FABRIC OF THE YULE MARBLE BEFORE DEFORMATION

A megascopic *s* plane, striking N5°E and dipping almost 90°, is shown by the "grain", i.e. by the dimensional orientation of the calcite grains. Petrofabric analysis indicates that this plane contains a strong concentration of lamellae into maxima, occupying in general the position that would be occupied by *e* planes belonging to the optic axes shown by the maxima in the optic axes diagrams.

It has long been known that *e* planes in calcite can act as operative[24] gliding planes in the calcite lattice, and the fact that these crystal planes lie in or near to the megascopic *s* plane of the fabric suggests that intragranular gliding movement along these *e* planes may have brought a large proportion of the calcite grains into their present preferred orientation.

In terms of petrofabric analysis the parallel surfaces along which the orienting of slip proceeds are defined by the axes *a* and *b*. Therefore the northward trending vertical plane occupied by the twin or translation lamellae would be the *ab* plane. By definition the axis *a* represents the direction of the movement and the axis *b* represents axis of slip, which is the normal to the movement direction. In the megascopic

[24] Operative is used here to denote the plane on which slip has occurred during the orienting process by which the fabric of the Yule marble was formed. Cf. Gough, H. J.: Crystalline structures in relation to the failure of metals, especially by fatigue. Am. Soc. for Testing of Materials, **33**, pt. 2, 18, 1933.

s plane (*ab*) there is nothing to determine the relative positions of *a* and *b*. The normal to the slip plane is the fabric axis *c*, which corresponds to the east-west direction and to the main lamellae maximum in the diagrams. The main slip plane of the fabric, (*ab*), established by the lamellae maxima determined in fabric analysis, coincides with the megascopic "grain" of the fabric.

The fact that the ratio of the longer to the shorter grain axes in sections parallel to R is 3 to 1 as contrasted with 1.8 to 1 in the section parallel to P suggests that the maximum extension of material is in the north and south direction, which would be the fabric axis *a*. However confirmation of the position of *a* would require exact determination of the crystal planes occupying each lamellae maximum. This has not been done in this preliminary work and the present work indicates only that the directions joining the lamellae poles and the optic axes are in or close to the horizontal plane in nature, a conclusion that is supported by the orthorhombic symmetry in the test cylinder after deformation, which is described in Part II.

The position of the center of gravity in the dominant axes maximum on *one* side rather than on both sides of the fabric axis *c* establishes the monoclinic symmetry of the undeformed fabric.

In order to evaluate the changes in fabric that were produced by compression in the laboratory the existence of a distinct *s* plane striking nearly north and standing approximately vertical, together with a statistical preference of the optic axes for a position that is inclined at 64° to the *s* plane, is the important feature of the undeformed fabric. Recrystallization — consequent upon thermal metamorphism could expectably emphasize this *s* plane. Whether this recrystallization is a paracrystalline growth accompanying a movement of intragranular slip or whether it is a mimetic recrystallization recording a pre-existing anisotropy could only be decided after more detailed study of the fabric under the microscope.

For the present study of the effect of compression, the requirement of a comparatively simple internal grain fabric that can be definitely related to the direction of applied force in deformation is fulfilled by the fabric of the Yule marble.

(*To Be Continued*)

TWO ENDOCRANIAL CASTS OF CETACEANS FROM THE OLIGOCENE OF NEW ZEALAND

B. J. MARPLES

ABSTRACT. Two natural endocranial casts of Cetaceans from the Oligocene of New Zealand are described. No skeletal remains are associated with either of them. The larger closely resembles published figures of endocranial casts of Archaeocetes except in that its cerebellum is small and normal instead of being of immense size. The cerebral hemispheres are small, especially anteriorly, and apparently had an olfactory region. The smaller specimen more closely approaches the condition seen in Recent specimens. The cerebral hemispheres have no olfactory region and are rounded anteriorly, but they are far less swollen. The two specimens afford intermediate stages between the brain of the primitive mammal and that of the Recent Odontocete. It is suggested that the immense and unique cerebellum described previously in the brain of Archaeocetes might conceivably be a misinterpretation of a large vascular plexus.

IN the collection of the Otago Museum, Dunedin, New Zealand, are two natural endocranial casts belonging to Cetaceans from the Early Tertiary. The larger one (No. C.48.70) has no data attached to it, while the smaller (No. C.34.7) was collected at Milburn, Otago. There seems no doubt but that both are of Oligocene age. They were mentioned in a paper dealing with *Prosqualodon hamiltoni* by Benham, who pointed out that the larger one is roughly similar in size to the cranial cavity of the skull of this Squalodont, though the skull is not well enough preserved for any of the details to be compared. The only literature on the endocranial casts of cetaceans available has been the papers of Elliot Smith and of Dart on the brains of Archaeocetes. Dart also figures and discusses an endocranial cast of *Prosqualodon davidi* from the Miocene of Tasmania. The present specimens are so unlike those in the literature that it seems desirable that they should be described, and I am indebted to the Director of the Otago Museum for permission to do so.

The larger specimen (Fig. 1), as preserved, is 145 mm. long, 148 mm. wide and 89 mm. high, and it has a volume of approximately 670 cc. It is broken off transversely at the anterior end and obliquely in the region of the medulla, while a portion is missing on the right side. The rest of the surface is well preserved and the impressions of many bloodvessels are clearly visible. The broken surface at the anterior end

forms a roughly equilateral triangle with sides about 50 mm. long. The dorsal angle runs back for some 35 mm. as a sharp ridge, the cerebral hemispheres swelling gently on either side.

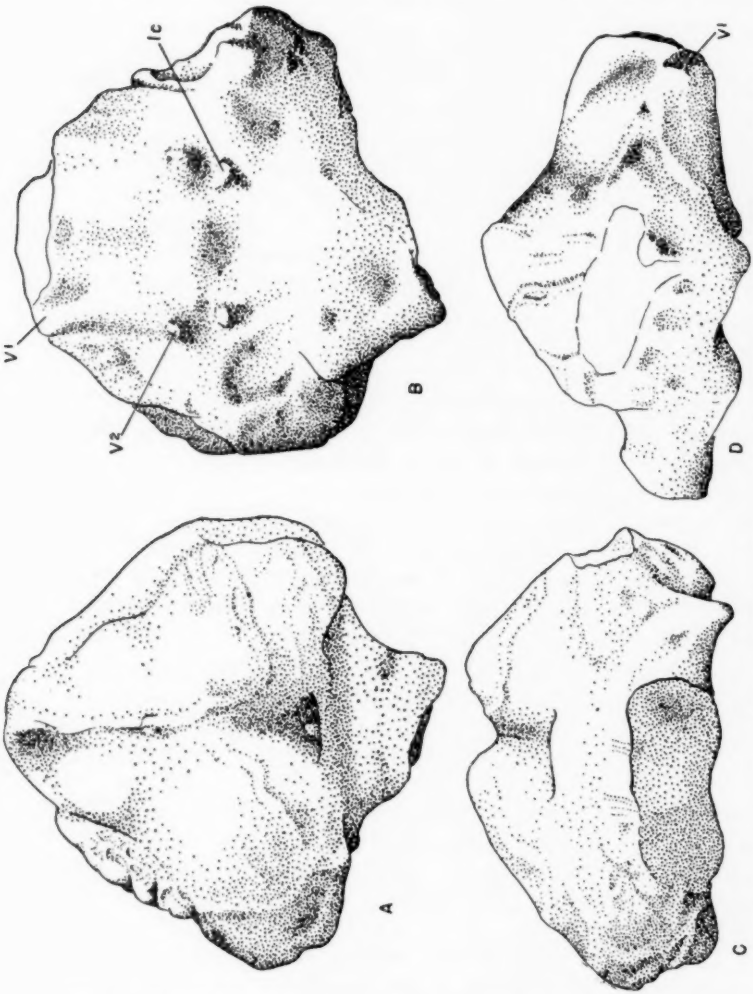

Fig. 1. Natural endocranial cast of Oligocene Cetacean from New Zealand. Larger specimen, No. C.48.70. Actual length 145 mm. A. Dorsal side. B. Ventral side. C. Posterior side. D. Right side. I.C. Internal carotid. V.1. Maxillary branch of trigeminal nerve. V.2. Mandibular branch of trigeminal nerve.

Indications of the sagittal sinus are visible in the middle line posterior to the ridge, and it extends into a deep V-shaped groove between the posterior regions of the cerebral hemis-

pheres, which rise on each side into rather sharp conical projections. Still more posteriorly the median groove widens out into a triangular depression bounded behind by a sharp transverse ridge. This depression presumably indicates the position of the tentorium cerebelli.

The cerebral hemispheres are low and narrow anteriorly, but expand rapidly both sideways and upwards towards their posterior ends. A shallow lateral depression separates a slight anterior swelling from the high conical region behind. The surface of the posterior half, as far forward as the highest peak, is covered with a network of bloodvessels, some of which are indicated in the figures. The best marked is a vessel which takes a curving course outwards from the sagittal sinus, passing posterior to the peak of the cerebral hemisphere. A larger, but less clearly defined vessel, runs from the region of the ridge behind the tentorial depression anteriorly round the lateral corner of the cerebral hemisphere. The details on the sides of the cast are not clear. Lying alongside the anterior half of the cerebral hemisphere is an irregular mass which seems to be composed of bloodvessels and appears to be connected with the posterior cerebral vessel and below with a large vessel which emerges between the cerebral hemisphere and cerebellum. This irregular mass is separated medially from the cerebral hemisphere by a groove, and is divided into three lobes by two oblique dorso-ventral grooves. Small fragments of bone still adhere to the cast in these grooves. The anterior end of the lateral irregular mass is broken off and lies adjacent to the corner of the anterior triangle as a small triangle about 10 x 15 mm.

The posterior region of the cast is broken off obliquely and only extends some 45 mm. behind the transverse ridge. From the ridge the dorsal surface sweeps smoothly down with only a slight transverse swelling and a few fine longitudinal bloodvessels. The cerebellar region extends obliquely downwards and forwards under the overhanging posterior edge of the cerebral hemisphere.

The ventral surface of the cast is broad and flat, its most conspicuous feature being a low transverse swelling slightly anterior to the middle. Posterior to the ends of this are small elevations apparently showing the positions of the internal carotid foramina, and lateral to these the large bloodvessels

come from the groove between the cerebellum and cerebral hemispheres and turn outwards towards the lateral irregular mass of bloodvessels. Smaller vessels appear from the same groove and also run laterally. Lateral to the ends of the transverse swelling are elevations probably representing the foramina for the mandibular branch of the trigeminal nerve, while the maxillary branch and the optic nerve appear to run forward at the lower corner of the anterior triangle.

Two artificial endocranial casts of Recent Odontocetes were available for comparison, one of *Lagenorhynchus obscurus* and the other of *Cephalorhynchus hectori* (fig. 2, E & F). A number of striking differences are at once apparent. In the fossil the main axis is straight while in the Recent specimens the anterior half is bent upwards at an angle of roughly 40°. The flatness of the ventral surface of the fossil is the more noticeable in that the lateral lobes of the cerebellum hardly extend below the ventral surface, while in the Recent casts they are much larger and more rounded and extend 15-20 mm. below it. The whole of the Recent cerebral hemisphere is more rounded and the anterior end is without the prismatic appearance of the fossil, while there is no sign of the lateral irregular mass of bloodvessels. Apart from these differences the fossil and Recent casts are easily comparable and the cerebral bloodvessels have the same course. The vessel emerging between the base of the cerebral hemisphere and the ventral anterior corner of the cerebellum runs round the back of the cerebral hemisphere on to the cerebellum near the tentorium and thence round to the ventral side of the medulla, while the middle cerebral vessel runs round over the apex of the cerebral hemisphere to the sagittal sinus. On the ventral surface, the internal carotid foramen and that for the mandibular branch of the trigeminal nerve are similarly situated.

The differences between the size and shape of the cerebral hemispheres and cerebellum in the fossil and the Recent specimens are such as one would expect in comparing the brains of Oligocene and Recent members of the same group of mammals. The difference at the anterior end seems to be due to the loss of the olfactory sense in the Recent Odontocete and perhaps also to the telescoping of the skull.

On comparing the fossil cast with the figures given by Elliot Smith and Dart of the endocranial casts of *Archaeocetes*, a

very strong general resemblance is at once apparent. The cerebral hemispheres of the Archaeocete are low and rounded anteriorly, and there is a dorsal ridge leading to a prismatic anterior end, formed by the olfactory peduncles and anterior nerves. On each side is an irregular mass, interpreted by Dart as a huge Gasserian ganglion covered by middle cerebral vessels. The posterior part of the Archaeocete cast rises to a peak, superficially much as does the present specimen.

The peculiarity of the Archaeocete brain lies in the cerebellum. This is an irregular transverse mass rising high above the cerebral hemispheres and extending down the sides in what are referred to by Dart as the paraflocculer lobes. To quote Elliot Smith, "perhaps the most striking feature of the brain of *Zeuglodon* is the extreme disproportion between the size of the enormous cerebellum and the diminutive cerebrum. In this respect the fossil brain presents a most marked contrast to that of all Recent mammals, and especially to that of the Cetacea." Much discussion has centered on the size of the cerebellum, and its relation to the systematic position of the Archaeocetes and their mode of life.

As pointed out above, if this information had not been available no difficulty would have been experienced in comparing the specimen with the Recent casts, its cerebellum being quite similar though relatively smaller (fig. 2). In view of the published information about the Archaeocete cerebellum and the close similarity in shape between the Archaeocete cast and the present one, a close reëxamination was made. There seems no doubt but that the whole of the anterior portion of the cast represents the cerebral hemispheres. A smooth continuous surface is visible with no trace of a transverse tentorium in front of the highest part, while there is one posteriorly, exactly as in Recent specimens. The elevated portions are separated by a deep sagittal groove as one would expect if they are cerebral hemispheres but not if they are cerebellum, and this is also visible in some of Dart's figures. The relations of the bloodvessels are also exactly as in the Recent specimens.

Unfortunately nothing is known of the origin of this specimen and Archaeocetes, Squalodonts and Cetotheres are all present in the Early Tertiary of New Zealand. The skull of *Prosqualodon hectori* is not sufficiently well preserved to show what was the shape of its brain, and the endocranial cast of

Prosqualodon davidi figured by Dart is quite unlike the present specimen. The balance of evidence, except for the condition of the cerebellum, seems to point to the present cast belonging to an Archaeocete. If it could be shown that the cerebellum of the Archaeocete was in reality a small normal one, the history of the Cetacean brain would be much simplified and the present specimens would fit readily into it. It is of course impossible to determine anything definite without examination of the specimens, but several points in the published figures and descriptions suggest that an alternative explanation is conceivable. The peculiarity of the Archaeocete structure is exemplified by Elliot Smith's statement, "behind the part which I have just described as the cerebrum there is a large irregular mass of a very peculiar shape, not exactly comparable with the condition occurring in any other brain known to me." Close examination, however, convinced him that it formed part of the cerebellum. Examination of Dart's figures shows

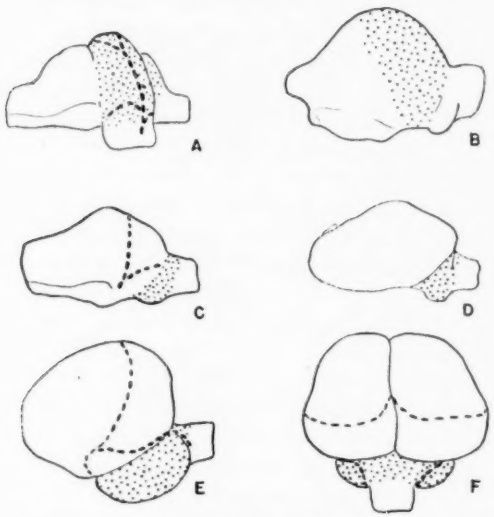

Fig. 2. Diagrams of endocranial casts of Cetaceans reduced to approximately the same size. Cerebellar region dotted, bloodvessels in broken lines. A. Left side of *Zeuglodon osiris* (bloodvessel from *Prozeuglodon atrox*), after Dart. Middle Eocene. B. Left side of *Prosqualodon davidi*, after Dart. Miocene. C. Left side of larger specimen. Oligocene. D. Left side of smaller specimen. Oligocene. E. Left side of *Cephalorhynchus hectori*. Recent. F. Dorsal side of *Cephalorhynchus hectori*. Recent.

that this region has a very irregular surface, due to the presence of either numerous small sulci or of bloodvessels. In some specimens there is a deep sagittal groove. It seems possible that this mass represents, not an immense anterior development of the cerebellum, but one of the retia mirabilia which are known to occur in Recent Cetaceans. Ommanney, describing these structures in the cervical region of *Balaenoptera* states that "up to the foramen magnum the neural canal is filled with a plexus, which is entirely venous, embracing the spinal cord and entering the skull through the foramen magnum to form a vascular mass against the hinder surface of the brain." In support of this suggestion is the fact that the corresponding region of the present specimen is covered with the impressions of bloodvessels, though not so thickly as to obscure the outline of the cerebral hemispheres. In Dart's figure of *Prozeuglodon atrox* the transverse sulcus anterior to this mass is very slight, while a bloodvessel runs over its apex very much as one does over the cerebral hemisphere of the Recent cast and of the present specimen. Further support to the vascular theory is the statement by Kellogg that the vertebrarterial foramina in the cervical vertebrae of *Basilosaurus cetoides* are very large, and that the main arterial supply to the brain of Recent Odontocetes is by this route.

The smaller specimen (fig. 3) is 88 mm. long, 89 mm. wide and 50 mm. high, and is asymmetrical, being strongly skewed over to the right. Its volume is approximately 200 cc. The cerebral hemispheres are low anteriorly, rising to a rounded elevation behind, the highest part being much less acutely pointed than in the larger specimen. The surface is smooth and without bloodvessels except for a few small ones entering the sagittal sinus. The anterior ends of the cerebral hemispheres are rounded and between them is a striking hexagonal projection whose concave anterior face contains traces of bone. No comparable depression was observed in several Recent porpoise skulls, and the shape of this part of the cast is quite unlike that of the larger one. Dart figures a conical anterior projection on the cast of *Prosqualodon davidi*, which he refers to as the olfactory peduncle. On the left side is a large mass somewhat ridged on its surface in a way suggestive of bloodvessels. There are traces of bone in the groove between this mass and the cerebral hemisphere. No transverse tentorial

depression is visible posterior to the cerebral hemispheres and the details of the posterior region are obscure.

The ventral surface is well preserved as a smooth undulating surface, all approximately in one plane. In the centre are several elevations and depressions, the largest apparently

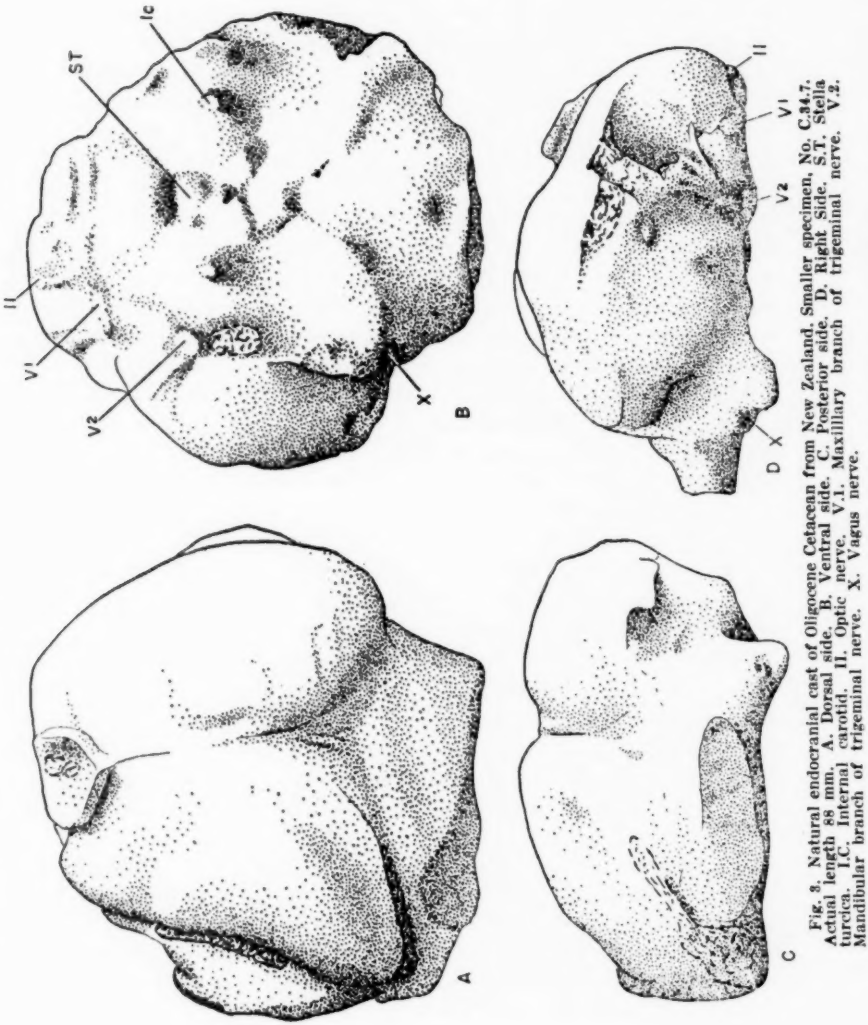

Fig. 3. Natural endocranial cast of Oligocene Cetacean from New Zealand. Smaller specimen, No. C.34.7. Actual length 68 mm. A. Dorsal side. B. Ventral side. C. Posterior side. D. Right Side. S.T. Stella turcica. I.C. Internal carotid. II. Optic nerve. V.1. Maxillary branch of trigeminal nerve. V.2. Mandibular branch of trigeminal nerve. X. Vagus nerve.

representing the sella turcica, and laterally there are elevations indicating the carotid foramina. Postero-laterally there is the elevation below the cerebellum and on its posterior surface is the impression of a foramen, possibly that for the vagus nerve. Anterior to this elevation is a deep depression containing fragments of bone on the right side of the cast, and anteriorly again are two elevations apparently representing the foramina for the mandibular and maxillary branches of the trigeminal nerve. At the anterior end on the right side can be detected what is probably the foramen for the optic nerve. The arrangement of these features is not unlike that seen on Recent endocranial casts, though in these they are more crowded together.

The smaller cast seems to represent a brain more closely resembling that of a Recent Odontocete than does the larger one. It differs from the Recent endocranial cast in being flat on the ventral surface, in having a relatively smaller cerebellum and very much less expanded cerebral hemispheres. It differs from the larger cast principally in the more rounded cerebral hemispheres especially at the anterior end where the cast is not drawn out into the prismatic anterior region. A remarkable feature is its very small size, 200 cc., and it seems likely that it belonged to a young individual. All the known New Zealand Odontocetes of camparable geological age are considerably larger, and according to Dart the volume of the endocranial cast of *Prosqualodon davidi* from the Miocene of Tasmania, is approximately 750 cc. Dart comments on the fact that this volume is slightly less than that of the endocranial cast of the Eocene *Zeuglodon intermedius*. He maintains that this is sufficient, in accordance with the "law of increasing brain weight" put forward by Marsh, to show that the Zeuglodont cannot have been ancestral to the Squalodont, but that the ancestor must have had a brain capacity very much less. Edinger, however, as a result of a study of the phylogeny of the horse brain, criticizes Marsh's law.

The larger specimen is interesting in the light of Edinger's findings in connection with the evolution of the horse brain. She showed that in *Eohippus*, where the skeletal characteristics already clearly foreshadowed the line of descent leading to the horse, the brain was completely unspecialized and comparable with only the most primitive of living mammals, such

as the opossum *Didelphys*. As she says, "the outstanding characters of the skeleton place *Eohippus* with the Equidae; the osteologist can see the future horse in this Lower Eocene form. The brain connects *Eohippus* only with the past. The ancestral brain, an unspecialized mammalian brain, was held over in the Equid body. No features of this brain signal the future." The cerebral hemisphere of the larger cast almost resemble those of *Eohippus*, though more expanded posteriorly so that the mid brain and cerebellum are less conspicuous. Assuming that the larger cast belongs to an Archaeocete, it is tempting to speculate as to whether the specialization of the bodies of these whales for aquatic life had taken place while the skull and especially the brain remained in a primitive condition. In the Odontocete, telescoping of the skull, loss of olfactory sense and enlargement of the cerebral hemispheres seems to have already taken place by Oligocene times, to judge from the smaller specimen, while in Recent times the cerebral hemispheres and cerebellum are greatly enlarged and exhibit the greatest degree of convolution of any brain. It is clearly recognized, however, that this interpretation of the present specimens does not fit in with those of Elliot Smith and Dart for the Archaeocete and Squalodont endocranial casts at their disposal, and further material must be awaited.

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STRATIGRAPHY AND TRILOBITE FAUNAL ZONES OF THE GARDEN CITY FORMATION, NORTHEASTERN UTAH

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ABSTRACT. The Garden City formation is widely distributed in northeastern Utah and the adjacent portions of southeastern Idaho, ranging in thickness from about 1,200 feet on the east to 1,800 feet on the northwest of the Logan quadrangle. As a lithologic unit it is easily distinguished from the dolomite of the underlying St. Charles formation and from the shales, siltstones, and quartzites of the overlying Swan Peak formation.

The Garden City beds can be divided into two members, the lower, comprising approximately two-thirds of the formation, being composed of numerous alternations of interbedded and interlensed intraformational conglomerates, and crystalline, aphanitic, and muddy limestones. The upper member is characterized by its high content of black chert nodules, stringers, and "interbeds" occurring for the most part in irregularly laminated, aphanitic limestone and dolomitic limestone.

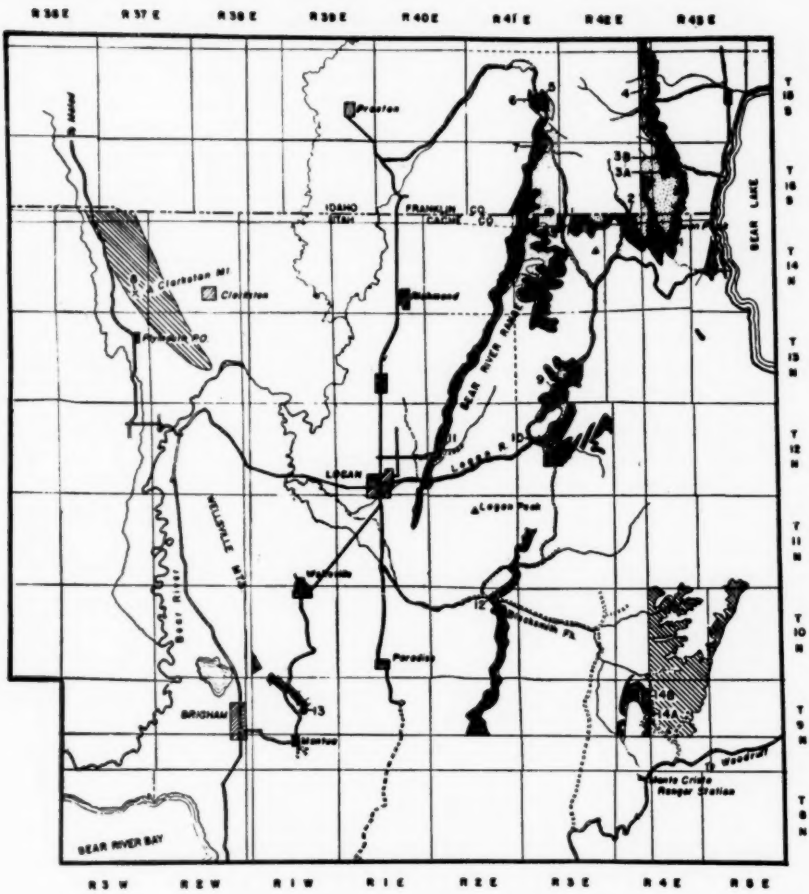
Faunal zones near the base and top of the formation indicate that its lower and upper boundaries vary little, if at all, in age within the area studied. A sequence of 12 faunal zones, distributed throughout the formation, indicate it to be mostly Canadian in age and contemporaneous with at least a part of the Pogonip limestone of Nevada. The upper 30 to 50 feet are faunally allied with the overlying Swan Peak formation and are almost certainly of Chazyan (Joins) age. On the basis of trilobites the lower 60-130 feet (including faunal zone "B") are correlated with the Tribes Hill and Stonehenge formations of the East.

The prolific trilobite fauna of the Garden City beds includes more than 80 species, detailed descriptions of which will be presented in a future publication.

The Swan Peak formation, now known to be composed of a more varied lithology than the original definition suggests, is over 550 feet thick in the northwest corner of the area studied, wedging-out completely to the southeast. Although the nature of its contact with the Garden City strata is apparently gradational to some degree, evidence for the direction of transgression of the younger detrital sediments is not clear in this region; such evidence must be sought in the western Utah and Nevada sections of the Pogonip formation and Eureka quartzite.

INTRODUCTION

IN 1913 the name "Garden City limestone" was given by Richardson to strata of Early Ordovician age in northeastern Utah and southeastern Idaho. These beds, which bear ample evidence for shallow water deposition, vary in thickness from 1,200 feet to 1,800 feet. As a result of the present study, to date limited to 14 strategically located sections within the area bounded by parallels 41°30′ and 42°10′ and meridians 111°20′ and 112°20′ (fig. 1), it has been possible to divide the formation into two lithologic members. A special search



AREAL DISTRIBUTION OF THE GARDEN CITY AND SWAN PEAK FORMATIONS

in Logan and Randolph Quadrangles, Utah, and southern Montpelier and Preston Quadrangles, Idaho.

Scale: 0 1 2 3 4 5 6 7 8 9 10 MILES

BOISE AND SALT LAKE MERIDIANS

GARDEN CITY FM. SWAN PEAK FM. UNDIFFERENTIATED LOWER PALEOZOIC

COMPILED FROM
BUTLER ET AL., 1920
GARFIELD, 1937
RICHARDSON, 1941
WILLIAMS, 1948

Figure 1. Index map of the area studied, indicating the positions of stratigraphic sections and collecting localities.

for silicified fossils, suitable for etching, has resulted in the discovery of more than 80 species of trilobites; these with other elements of the fauna are the basis for the designation of 12 faunal zones within the formation. Because of the nature of its contact with the Garden City beds, some attention was given to the overlying Swan Peak formation.

As originally defined by Richardson (1913, p. 408-409) with its type section in Garden City Canyon, Sections 3, 4, and 10, Township 14 North, Range 4 East, the Garden City formation was stated to consist of a "succession of thick and thin bedded gray limestone approximately 1,000 feet thick" and to be characterized by the "presence throughout the formation of a conglomerate or breccia consisting of elongate bits of limestone up to 2 or 3 inches in length, irregularly imbedded in a matrix of similar composition." Richardson further noted that the formation apparently overlay the St. Charles formation disconformably and was overlain by the Swan Peak "quartzite" conformably (1913, p. 408). It was considered to be of Beekmantown age.

Mansfield recognized and mapped the formation in the Fort Hall Indian Reservation (1920, p. 32 and Plate III), in the Portneuf Quadrangle (1929, p. 19), and in the Montpelier Quadrangle (1927, p. 57) in Idaho. In his report on the last of these he increased Richardson's thickness to 1,250 feet. In 1934 Kirk (p. 456) suggested the contemporaneity of the El Paso limestone with the Garden City beds.

Because of a series of confusions, stemming from erroneous interpretations of the relation between the St. Charles and Garden City formations (Williams, 1948, p. 1135) Richardson (1941, pp. 13-14) incorrectly increased the thickness of the formation in the Randolph Quadrangle to 1,900 feet. This error is rectified by Williams in his recent account of the Paleozoic rocks of the Logan Quadrangle (1948, pp. 1135-1137); in his report Williams notes the presence of "thick beds of dark gray dolomite at the top of the St. Charles formation," which are good stratigraphic markers, and for the first time recognizes the multiple lithology of the overlying Swan Peak beds.

In the Clarkston Mountain area (Loc. 8, fig. 1), originally mapped as undifferentiated Paleozoic by Butler et al. (1920,

Pl. IV), the Garden City and Swan Peak formations are present, as they are in the southwest corner of the Randolph Quadrangle (Loc. 14, fig. 1), mapped in a similar fashion by Richardson (1941). The two formations also appear on reconnaissance maps prepared by the members of the Yale summer course in Geology during the 1946 and 1947 sessions in the southern portion of the Preston Quadrangle.

The writer is indebted to his wife, to J. Stewart Williams, to John Masters, and to William Swire for their assistance in the field; for their interest and suggestions concerning the study of the stratigraphy and fauna he is equally grateful to Prof. Carl O. Dunbar, James L. Wilson, C. R. Longwell, B. F. Howell, J. T. Gregory, K. M. Waage, H. L. Whittington, G. A. Cooper, W. A. Bell, and John Rodgers. The study was made possible by the Charles Schuchert Memorial Fellowship, and this paper is a part of a dissertation presented in partial fulfillment of the requirements for the degree of Doctor of Philosophy at Yale University.

STRATIGRAPHIC SUMMARY

Lithology and Thickness of the Garden City Formation. Lithologically the Garden City formation can be divided into two members, the lower two thirds being predominantly intraformational conglomerate and the upper third being very cherty. The lower member is a complex of interbedded layers of intraformational conglomerate, muddy limestone, crystalline limestone, and limy siltstone, with some layers of compact, thinly laminated, cryptocrystalline limestone. No sequence of beds that can be identified in more than one locality has yet been identified within this member; most of the beds appear to thicken, thin, lens-out, or change lithology within short distances. Only a few resistant, laminated, aphanitic limestones are at all persistent.

In addition to intraformational conglomerate, some of the coarsest of which is admirably exposed on a dip slope 87 feet above the base at Locality 11 (pl. 1, fig. 1), other characteristics suggesting a shallow water origin for the formation are channel fills (a good example 70 feet above the base at Locality 5), ripple marks (best exposed on a dip slope, 85 feet above the base at Locality 11; pl. 1, fig. 1), and cross-bedding in coarsely crystalline limestone (a good example at Locality 9; pl. 1, fig. 2).

Another feature of the lower member is the random scattering of white to light gray chert stringers in the lower 300 feet; these are best exposed at Locality 7, about 240 feet above the base of the formation, on several dip-slope surfaces, where they lie in rectilinear patterns strongly suggesting emplacement controlled by joints. These lower cherts are not to be confused with the black chert of the upper member from which they are quite distinct.

In the middle third of the formation the percentage of intraformational conglomerate (pl. 2, fig. 1) is considerably higher than in the lower third, where shaly and muddy limestones comprise much of the section. As in the lower third, individual beds not only lens-out, but their lithologies may change within several feet. In this portion there are in most localities several beds of a more persistent nature, composed of crudely laminated, crypto-crystalline, resistant limestone (pl. 2, fig. 2).

The upper one-third of the Garden City formation, the upper member, is sufficiently uniform throughout the area studied to be recognized with little more than a glance. Unlike the seemingly endless alternations and variations of lithologies of the lower two-thirds, this upper member is made up predominantly of thick, generally resistant beds of crypto-crystalline, dark limestone, composed of thin, discontinuous, very irregular laminae, one-half to one inch thick. The laminae are separated in most cases by paper-thin partings of mud, which give weathered vertical surfaces a peculiar wavy appearance (pl. 2, fig. 2; note uppermost layer above black chert, pl. 3, fig. 1).

The most striking feature of the upper member is its high chert content. The chert is black and in the form of nodules, stringers, and "discontinuous beds," oriented roughly parallel to the laminae of the crypto-crystalline limestones (pl. 3, figs. 1 and 2). In all the studied localities where the upper member is present there is one zone in which chert makes up approximately 50 percent of the exposed rock; above it the percentage slowly dwindles, until at the very highest limestone or dolomitic exposure very little or no chert is present. That this upper cherty zone has stratigraphic significance appears certain, not only because of its areal extent, but also because of its contained fauna.

Some rather coarsely crystalline dolomite is found at the very top of the formation at most of the studied localities and has been recognized by Duncan (personal communication) at Blacksmith Fork and St. Charles Canyon. That this dolomite is a *bona fide* sedimentary unit is open to question; at Localities 11 and 13 there is some suggestion that the replacement of limestone and dolomitic limestone by dolomite is secondary along faults or fracture zones. At Locality 1 there is undeniable evidence of the replacement of a bed of intraformational conglomerate by dolomite, but because of imperfect exposure it is not certain whether this is a case of penecontemporaneous or a much later secondary replacement. It should be noted that the irregular line separating the symbol for black chert and that of dolomite and dolomitic limestone in the diagrammatic sections (fig. 2) at Localities 13A and 11 represent irregular gradations, not unconformities.

At its type section (Loc. 1, fig. 1) the Garden City formation is 1,225 feet thick and is apparently little diminished or increased in a north-south direction. To the west, however, it attains 1,440 feet in Hillyard's Canyon (Loc. 5) and 1,760 feet at Clarkston Mountain (Loc. 8).

The Lower Boundary. In this study the base of the Garden City formation is placed below the lowest limestone bed which occurs above the thick, brownish-weathering, dark-gray dolomite at the top of the St. Charles formation (Williams, 1948, p. 1135). This lithologic definition of the lower limit of the formation appears to hold approximately the same position in a time sense throughout the area.

The Upper Boundary of the Garden City Formation. The upper boundary of the formation is not as easily determined as earlier descriptions imply; all of these, except Williams' state that the formation is overlain by the Swan Peak "quartzite." Actually, in neither the northwestern part of the Randolph Quadrangle (which includes the type sections of both formations) nor to the south is the relation so simple.

As recorded by Williams (1948, p. 1136) the Swan Peak formation is not entirely quartzitic. Its appearance at the type section (Loc. 1) is misleading, for the lower half of the formation is masked by rusty-colored, silty, sandy, and badly weathered quartzite rubble. At Locality 2, three miles to the west-northwest, there is an excellent exposure along the

small gorge of Beaver Creek. Here one can see the thick massive, vitreous quartzites of the upper part overlying thinner, less firmly cemented, and more fossiliferous beds. Progressively lower in the section the quartzites thin, and more and thicker interbeds of shale are present. Limestone lenses occur in the lowest shales with only a few thin, calcareous sandstone layers. There is little doubt that the black shales exposed at Locality 2 are present but hidden by mantle and float at the type section, explaining the failure of previous workers to recognize the multiple lithology of the formation.

Southward the upper quartzites thin-out. At Locality 10 (fig. 8) they have decreased by half, and at Locality 12 (Blacksmith Fork) only thin interbeds of sandstone, shale, and lenticular limestones are present. At Locality 14A (Bucks Spring Road) the formation is entirely absent. To the west at Clarkston Mountain (Loc. 8) 50 feet of sandstones with calcareous cement directly overlie the Garden City formation. Although no shales were observed near the base by this author, a short interval overlying the sandstones and underlying the upper thick quartzites is covered in much the same manner as the lower part of the type section and may represent shale beds.

Since the contact is gradational from dolomitic limestone through shale to quartzite in some localities and since Ulrich and Cooper (1938) suggested in several instances that a part of one formation might be a facies equivalent of the other it was felt that the older unit might be thickening southeastward at the expense of the Swan Peak beds which disappear in that direction. There is, however, some faunal evidence which indicates that this is not the case.

The upper boundary of the Garden City formation is placed below the lowest shale, siltstone, sandstone, or quartzite bed of the Swan Peak sequence, although limestone lenses are encountered in some places above this horizon. This is the basis on which Williams (1948) mapped the formation in the Logan Quadrangle and the one found most satisfactory during this investigation.

FAUNAL ZONES AND CORRELATION

Although the fossils collected from the Garden City and Swan Peak beds include sponges, graptolites, pelmatozoans, brachiopods, gastropods, nautiloids, trilobites and ostracods,

time has permitted a study of the trilobites only. A few brachiopods have been identified specifically, but most of them only generically. The graptolites have been compared cursorily with forms they resemble.

To date over 80 species of trilobites have been found in these two formations, all but two coming from the Garden City beds. In most cases the specimens are silicified and number over 25 per species. In a few instances forms are so distinctive that species have been based on much smaller samples.

As stated above, it appears probable that 12 *bona fide* faunal zones, designated by the letters "A" to "L" below, can be recognized within the Garden City formation; these are not founded entirely on trilobites. Further studies may show that too many zones have been set-up or that one or two should be based on different species. Since most of the trilobites are new, no attempt is made at this time to enumerate them in detail. The fauna of the Swan Peak beds is placed in zone "M."

Briefly, the zones characterized by previously described genera and species or by especially distinctive forms are set-forth below:

Swan Peak formation:

Zone "M"—

Eleutherocentrus petersoni Clark
Didymograptus cf. *bifidus* (Hall)
Orthis swanensis Ulrich and Cooper
Anomalorthis sp.

Numerous ostracoda, possibly referable to *Leperditia*

In addition this zone includes a distinctive, undescribed trilobite genus which has been collected also from the Upper Pogonip formation in Nevada and from the Lower Simpson group in Oklahoma; specimens from both are in the collections of the U.S. National Museum. Those from the Oklahoma area are in collections from U.S.G.S. Localities 360K2 (labelled "Oil Creek formation") and 199t (labelled "Joins"). In both, the genus is associated with *Eleutherocentrus* and ostracoda which are very close to those found in the Swan Peak formation.

Garden City formation:

Zone "L"—

Anomalorthis sp.

Blastoidocrinus cf. *carchariaedens* Billings
Syntrophopsis transversa Ulrich and Cooper
Rhynchocamara n. sp.
Orthis sp. (close to *O. subalata* Ulrich and Cooper)

Zone "K"—
Blastoidocrinus cf. *carchariaedens* Billings
Nothorthis sp.
Diparelasma sp.
Hesperonomia sp.

Zone "J"—
Kirkella cf. *vigilans* (Whittington) (equalls so called *Asaphus curiosus* of other authors)
Eleutherocentrus n. sp.
Kawina n. sp.
Goniotelus ? sp.
Hesperonomia dinorthoides Ulrich and Cooper
Syntrophopsis cf. *polita* Ulrich and Cooper
Diparelasma sp.
Tritoechia n. sp.

Four other trilobite genera characterize this zone. One is an asaphid with a peculiarly fringed hypostome. The second is a proparian possessing a nasute anterior rim with a median pit between the rim and glabella. A Komaspid without glabellar furrows but with a pair of large nodes, one on either side of the glabella near the occipital furrow is the third, while the fourth is a very small *Dimeropyge*-like form.

Zone "I"—
Retiograptus sp.
Diparelasma cf. *typicum* Ulrich and Cooper
Hesperonomia sp.
Goniotelus sp.

This zone is based on collections from a single locality (3B); it may eventually be shown to belong in the base of zone "J."

Zone "H"—
Didymograptus cf. *nitidus* (Hall)
Dictyonema, 2 sps.
"*Xenostegium*" ? cf. *goniocerum* (Meek)

Zone "G"—

This is the most complex of the established zones. It is based on the occurrence of an *Apatokephalus*-like genus in which the anterior marginal furrow is tangent with the dorsal furrow in front of the glabella, pits are lacking in the marginal furrow, and each palpebral lobe possesses a curving furrow proximal to

Fig. 1—Coarse intraformational conglomerate bed overlying ripple-marked surface (left side), 87 feet above the base of the Garden City formation, Locality 11.

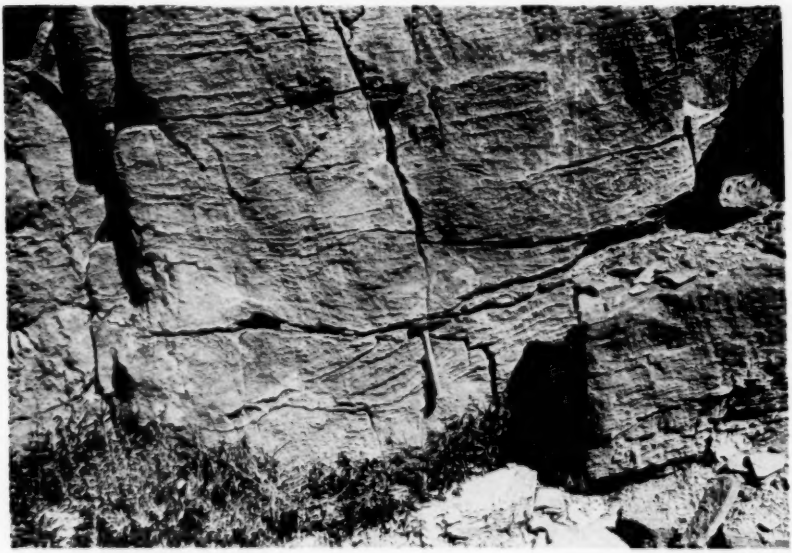


Fig. 2—Cross-bedding in a coarsely crystalline limestone bed, approximately 500 feet below the top of the Garden City formation, Locality 9.

Fig. 1—A large float-block of intraformational conglomerate, 530 feet above the base of the Garden City formation, Locality 1.

Fig. 2—A thick resistant bed of crudely laminated, crypto-crystalline limestone, 215 feet above the base of the Garden City formation, Locality 5. Note weathered vertical surface.

Fig. 1—Irregularly laminated, crypto-crystalline limestone with "interbedded" discontinuous black chert "bands" approximately 200 feet below the top of the Garden City formation, Locality 3B.

Fig. 2—Black chert nodules, stringers, and "layers" in fine-grained dolomitic limestone, 200 feet below the top of the Garden City formation, Locality 8.

and nearly parallel with the normal palpebral furrow. Within the range of this form occur two species of *Protopliomerops*, on the basis of which an upper, "G(2)," and a lower, "G(1)," subzone are established. At the base of this zone a species is present which is apparently assignable to *Macropyge* Stubblefield. Near the top was found the only species assignable to *Jeffersonia*.

Zone "F"—

A total of 23 trilobite species have so far been recognized from this zone. These include four species of *Hystricurus* and one of *Protopliomerops*. It may include the highest occurrence of the former and the lowest appearance of the latter, but such a possibility cannot yet be considered a fact.

Zone "E"—

Eleven species comprise this zone, including three of *Hystricurus*; one form is very close to *Beltella* Lake and another appears to be intermediate between *Pilekia* and *Protopliomerops*.

Zone "D"—

Apheorthis cf. *meeki* Ulrich and Cooper
Leiostegium manitouensis Walcott

Zone "C"—

Nanorthis ? sp.
Syntrophina ? sp.
Symphisurina sp. (close to *S. spicata* Walcott)

Zone "B"—

Beliefontia sp.
Clelandia n. sp.
Hystricurus, 3 n. sps.
Symphisurina sp.
Xenostegium sp.

This zone is also characterized by a small genus with a *Remopleurides*-like cranidium, but with a pygidium possessing four or five pairs of dagger-like spines.

Zone "A"—

Nanorthis sp.
Symphisurina sp.
Hystricurus sp.
Bellefontia ? sp.

This zone is possibly not a valid one. The trilobite species appear to be distinct from those of corresponding genera in the higher zones, but these differences may be due in part to different methods of preservation.

Although the above listing and comments are far from inclusive, they will at least serve as a generalized preview of the faunal zones, which are to be presented in detail with full systematic descriptions in a future publication.

With no more information than that presented above and with the assistance of the Correlation Chart for the Ordovician of North America (Ordovician Sub-Committee, Geological Society of America) now in preparation, it is possible to come to a few conclusions concerning the dating of the Swan Peak and Garden City formations. Richardson (1913, p. 409) originally considered the former to be of Chazyan age; this dating has been questioned more recently because of the occurrence of *Didymograptus* cf. *bifidus* in the shaly portions (Williams, 1948, p. 1137). There is in this author's opinion little doubt that the Swan Peak beds are at least as young as the Joins formation of Oklahoma (see discussion of zone "M" above); this is corroborated by the presence of *Anomalorthis* in zone "L" below the top of the Garden City formation; that genus is not known in beds older than Joins according to G. A. Cooper (personal communication).

Similarly, the species of faunal zone "L" may indicate that the uppermost portion of the Garden City formation is also of Joins age; in this connection it is noted that *Blastoidocrinus* has never been reported in beds older than Chazyan. It then appears probable that the Canadian-Chazyan boundary must fall within the upper Cherty member of the Garden City formation, somewhere between zones "L" and "J." The single species of *Jeffersonia* from the upper part of zone "G" is so close to *J. missouriensis* Cullison that it suggests the correlation of its subzone with the Rich Fountain formation of the Ozarks.

Since faunal zone "B" is a typical Tribes Hill-Stonehenge assemblage, it is concluded that the Garden City formation runs the full gamut of the Lower Ordovician and that no major change took place in the conditions of sedimentation in this area until after the beginning of Chazyan (Joins) time.

Furthermore the occurrence of species which are apparently very close to *Macropyge* Stubblefield and *Beltella* Lake may indicate contemporaneity of zones "E" to "G" with the Lower Ordovician of Britain.

LOCAL STRATIGRAPHIC SECTIONS

No attempt is made here to record the detailed lithologies of the 14 sections which were measured and from which collections were made; instead a very generalized account of each section is given below, noting the presence and relative position of any of the discovered faunal zones.

Supplementing the material which follows, seven of the sections are represented graphically in figure 2; as drawn they are very generalized since none of the more detailed lithology is indicated. Position of faunal zones is shown to the right of each of the sections. It is reiterated that the boundary drawn between cherty and non-cherty beds in sections at Localities 11 and 13A are not unconformities, but gradational contacts.

Locality 1. *Swan Peak and Garden City Canyon* (E. ⅛, Sec. 10, and N.W.¼, Sec. 11, T. 14 N., R. 4 E.)

This is the type section of both the Swan Peak and Garden City formations. The Swan Peak formation is approximately 315 feet thick here; faunal zone "M" has been recognized in the interval 145-230 feet above its base. The lower 145 feet of the formation are masked by float.

The aggregate thickness of the Garden City formation at its type section is 1,225 feet, the upper 210 feet of which are assigned to the Cherty member. Only a single collection was secured from this member, 160 feet from the top of the formation; unfortunately silica replacement was so complete in the collected rock specimens that only a few fossils could be freed from the matrix. These belong to zone "J" or "K," but to which is not certain. Sponges are abundant in 18-foot intervals of massive, black, extremely aphanitic limestone 707-725 feet above the base of the formation, and large, orthoconic nautiloids four to five inches in diameter were found in aphanitic limestone 200 feet above the base. Faunal zone "B" was definitely found 50 feet above the base, but only a single species belonging to zone "A," a *Symphisurina*, was located approximately 20 feet above the top of the St. Charles formation.

Locality 2. *East side of Beaver Creek, immediately south of the Idaho-Utah state line.* (E. ½, Sec. 35, T. 15 N., R. 4 E.)

This locality was included to establish the presence of black

shale beds in the lower part of the Swan Peak formation, which are not exposed at the type locality two and one-half miles to the east. Approximately 340 feet of the formation are exposed, of which the lower 145 feet are composed of black, flakey shale, with scattered limestone lenses near the base. Both the shales and the lower quartzite beds are abundantly fossiliferous; faunal zone "M" falls here.

Because of faulting only the uppermost beds of the Garden City formation are exposed at this locality; as a result no attempt was made at measurement.

Locality 3. *Fish Haven Canyon*

The Swan Peak and Garden City formations are exposed on both sides of the canyon approximately 4 miles west of Fish Haven, Idaho. The sections measured were not satisfactory, because of the thickness of plant and forest covering. In order to obtain any indication of thickness and lithologies it was necessary to run two traverses and then attempt to piece the results together; unfortunately there are large gaps in both resulting sections which prohibit perfect correlation between the two. The two traverses are indicated on the index map (fig. 1) and on the diagrammatic sections (fig. 2) as Locality 3A (E. ½, N.W. ¼, and W. ½, N.E. ¼, Sec. 17, T. 16 S., R. 43 E.) and Locality 3B (N ½, Sec. 7, T. 16 S., R. 43 E.). The exposed thickness of the Swan Peak strata are believed to approximate 535 feet and that of the Garden City formation 1,245 feet. The thickness of the upper Cherty member of the latter is between 230 and 360 feet.

At Locality 3B, in addition to the usual species found in faunal zone "M" in the Swan Peak beds a mold is tentatively identified as *Anomalorthis* sp. Zone "L" was located within 100 feet of the top of the Garden City formation at this same locality, but only a single representative, *Syntrophopsis transversa* Ulrich and Cooper, was found at Locality 3A, within 50 feet of the top. The interval from 240 to 285 feet below the top of the Garden City strata at Locality 3B contains a fauna assigned to zone "I," while forms indicative of zone "H" occur in the next lower 80-foot interval. No fossils were collected from lower beds.

Locality 4. *St. Charles Canyon* (6 miles west of St. Charles, Idaho, on west side of canyon; Sec. 13, T. 15 S., R. 43 E.)

The Swan Peak formation attains a minimum thickness of

500 feet at this locality. An apparent thickness of over 1,550 feet for the Garden City beds is attributed by Duncan (personal communication) to repetition by faulting, causing a seemingly considerable increase over that at Localities 1 and 3 to the south. Faunal zone "J" was located within 150 feet of the top of the formation and zone "B" within 100 feet of the base; no collections were made.

Locality 5. *East side of Hillyard's Canyon* (1.8 miles north of the head of the canyon; S.E. ¼, Sec. 17, T. 15 S., R. 41 E.)

This locality and Locality 6 on the west side of the Canyon have provided the bulk of the trilobite faunas collected; both are more readily accessible than the type section of the Garden City formation and fossil preservation is far superior.

Although thinly represented 100 yards east of the top of the section by quartzite beds, only a thin veneer of rusty shale and silty "chips" of the Swan Peak formation overlies the Garden City beds at the measured traverse. Because of the thick vegetation separating the two points and the abundance of faults of large displacement along the canyon it is considered unwise to include any thickness for the younger formation here.

The thickness of the Garden City formation totals 1,440 feet of which the upper 370 feet belong in the Cherty member. The top 85 feet contain the fauna assigned to zone "L"; although zone "K" is present in the next lower beds the level of demarcation between it and zone "J" has not yet been satisfactorily established, probably because sampling was not definitive enough. The possibility also exists that zones "K" and "J" are intergradational. Both trilobites and brachiopods of zone "J" definitely occur throughout the lower 250 feet of the Cherty member.

Within the lower member of the formation faunal zone "A" was tentatively founded on a small collection from the base; zone "B" is present 75-85 feet, zone "C" is between 115 and 140 feet, and zone "D" appears in a thin interval 140 to 145 feet above the base. Only in a single one-foot muddy limestone bed, 305 feet above the base has the fauna of zone "E" been collected, while that of zone "F" has not been located to date in this section. Zone "G," with several of its subzones, appears from 428 to 920 feet above the bottom of the formation, and

the interval from 945 to 1,020 feet contains faunal zone "H."

Locality 6. *Crest of Ridge on west side of Hillyard's Canyon*

This section was measured for supplementary use with Locality 5; only the lower 750 feet of the Garden City formation is well-exposed. From here a prolific silicified trilobite fauna has been secured, from the same zones as at Locality 5 through zone "G" with the exception of "A," "C," and "D." The forms of zone "E" are abundantly represented within a considerably thicker interval, and those of "F," which were not located at Locality 5, are present in profusion.

Locality 8. *West side of Clarkston Mountain* (Sec. 25, T. 14 N., R. 3 W.)

This is the most northwesterly of the sections in the area studied. The base of the Garden City formation is exposed approximately 2,500 feet above the level of U.S. Highway 191. The Fish Haven dolomite overlies the Swan Peak formation disconformably at this locality.

The thickness of the Swan Peak beds totals 570 feet, the lower 50 feet being composed of calcareous quartz sandstone. Although 1,764 feet of Garden City beds were measured, it is barely possible that there may be some minor repetition of beds through faulting; because faults of large displacement were recognized on either side of and above the block on which the measured traverse was run, special attention was given this possibility. It is believed that the measured thickness is original.

At this locality the upper Cherty member of the Garden City formation is about 400 feet thick. Within 155 feet of the top representatives of both faunal zones "L" ad "K" were found but the boundary between the two is not as yet definite. Both trilobites and brachiopods of zone "J" are abundant in a 10-foot interval 245 feet from the top of the formation.

At the top of the lower member, from 1,135 to 1,340 feet above the base of the formation, specimens were collected from zone "H." Only 913 feet above the base a single specimen of *Kirkella* Kobayashi was secured. In the interval from 330 to 615 feet above the base a few forms assigned to zones "C" and "D" were located, but the two do not appear to be separable as easily as at other localities. Trilobites of fauna "B"

occur in scattered beds from 20 to 295 feet above the St. Charles formation.

Locality 9. *Twin Bridges Dugway, Logan Canyon* (N.W. ¼, S.W. ¼, Sec. 34, T. 13 N., R. 3 E.)

This locality is situated in the abandoned road-cut on the west side of U.S. Highway 89 at the north end of the Twin Bridges dugway. It was visited exclusively for the collection of graptolites. The exact stratigraphic position of the zone cannot be ascertained but it is estimated to be 500-600 feet below the top of the Garden City formation. Graptolites include two species tentatively assigned to *Dictyonema* and one species of *Tetragraptus* close to *T. quadribrachiatus.* A few feet above the graptolite beds a massive limestone strata contains abundant silicified sponges possibly referable to *Receptaculites.*

Locality 10. *Junction of the Logan River and its Right Fork* (N.E. ¼, Sec. 18, T. 12 N., R. 3 E.)

The Swan Peak formation and the upper 150-200 feet of the Garden City beds are exposed on the north side of the Right Fork; on the west side of U.S. Highway 89 the upper Swan Peak beds are well displayed.

Here the Swan Peak formation is 240 feet thick, a considerable decrease from its total to the north. Collections made from the top 100 feet of the Garden City strata were unfortunately lumped together; it is now evident that faunal zone "L" and zone "K" are both present in the interval.

Locality 11. *Green Canyon* (N. E. ¼, Sec. 18, and N. W. ¼, Sec. 19, T. 12 N., R 2 E.)

The complete St. Charles, Garden City, Swan Peak, Fish Haven sequence is exposed on both sides of the Canyon which cuts approximately at right angles across the strike of the beds. The lowest beds of the Garden City formation are found approximately 1,600 yards east of the Canyon's mouth.

Williams (1948, p. 1136) gives a thickness of 339 feet for the Swan Peak beds at this locality, a figure very slightly in excess of this author's measurement. The fauna of zone "M" is abundant in silty and sandy layers of the lower 180 feet and in limestone lenses interspersed throughout the lowest black shales.

The Garden City formation attains a thickness of 1,405

feet, of which the upper 365 feet belong to the Cherty member. Faunal zone "L" occurs within 50 feet of the top; zone "B" is approximately 125 feet above the base of the formation, and one of the sub-zones of zone "G" has been located 490 feet above the base.

Locality 12. *Blacksmith Fork, north side of Canyon* (S. ½, Sec. 2, T. 10 N., R. 2 E.; near power house)

The thickness of the Swan Peak formation here is considerably diminished to 105 feet, and none of the thick quartzites of the type section are present. None of the beds is over one foot thick; in general three- to six-inch quartzite and sandstone layers, two- to four-inch greenish shale layers, and one- to three-inch limestone lenses are interbedded. There are nearly as many limestone lenses near the top as quartzite and sandstone layers near the base. The formation has little surface expression, because of the unresistant nature of the shales and the silty character of the quartzites and sandstones.

The Garden City formation has been measured at this locality by Duncan, who found it to be 1,160 feet thick (personal communication). Although his data are in my possession, the opportunity has not arisen to study his fossil collections at Princeton University. Since Duncan's collecting did not include the upper 100 feet of the formation, this author secured specimens which have proved to be identical with those collected from the same interval at Locality 10.

Locality 13. *Round Hill, north of Mantua, Utah* (S.E. ¼, Sec. 10, and N. ½, Sec. 15, T. 9 N., R. 1 W.)

At this, the most southwesterly of the studied sections, the Swan Peak formation is 245 feet thick; massive quartzites comprise the upper 55 feet, thin beds of reddish quartzites and siltstones the next lower 30 feet, and olive-green shales with scattered sandstone layers the lower 160 feet. No better locality was found for the collection of species belonging to faunal zone "M," especially of *Didymograptus* cf. *bifidus*.

The Garden City formation totals 1,390 feet in thickness, with the upper Cherty member consuming the top 425 feet. Although faunal zones "L" and "K" were not located, beautifully silicified trilobites and brachiopods of fauna "J" were collected in the interval from 270 to 355 feet from the top of the formation; this collection also includes a few fragmentary specimens believed to be *Receptaculites*.

Collections made to date from the lower beds of the formation are not satisfactory for accurate correlation with other sections. Two poorly preserved trilobites were secured 230 feet above the base which are believed to belong in zone "E"; the forms taken from 90 feet above the bottom of the formation include *Hystricurus* cf. *cordai*, not found in any of the other sections, and a few specimens of *Nanorthis* and *Syntrophina*(?), which are considered to be the same as those from zone "C" at Locality 5.

Locality 14. *Davenport Hollow, north of Monte Cristo Ranger Station* (Between S.E. ¼, Sec. 5, and W. ½, Sec. 17, T. 9 N., R. 4 E.)

In almost every respect this is the least satisfactory of all the localities visited. Because of heavy vegetation and complex faulting no single section was found in which the entire Garden City formation could be measured. To tie-in the bottom and top of the section an attempt was made to trace a key bed for more than a mile between two traverses, resulting in a computed thickness of 1,185 feet for the formation; this figure is not considered reliable, but roughly indicates that the formation has changed little in thickness southward from its type section.

This locality's main point of interest is the absence of the Swan Peak formation. It was at first believed that a 20-foot interval of light brown, flakey shale and silty shale, which lies 70 feet below the Fish Haven dolomite, was equivalent to some of the lower shales of the Swan Peak. However, between these shales and the basal Fish Haven beds there is typical cherty limestone of the type found in the upper part of the Garden City formation, topped by four feet of brownish arenaceous dolomite. In this dolomite occurs a fauna which undeniably belongs to zone "L." Furthermore, the shales below contain a very distinctive proparian trilobite species which is especially characteristic of zone "J."

Within a 30 foot interval approximately 90 feet above the base of the formation specimens of two species of *Hystricurus*, one species of *Symphisurina*, and one species of *Syntrophina* were collected; little more can be told from these than that they lie below the upper limit of zone "F."

Interpretation of the Local Stratigraphy. During Early Ordovician and part of Chazyan time the Logan Quadrangle

and its environs were the locus of deposition of a great thickness of interbedded and interlensed calcirudites, calcarenites, and calcilutities, composing the Garden City formation. Intraformational conglomerates, ripple marks, and cross-bedding in the limestones of the formation attest to its shallow-water origin. Toward the close of the Early Ordovician large amounts of silica were apparently supplied to the area, leading to the formation of an upper Cherty member.

Although the Garden City beds are some 500 feet thicker on the west at Clarkston Mountain than at the type area, there is in general relatively little change in the vertical dimension throughout the studied area. To account for the eastward decrease in thickness the possibility was at first contemplated that the oldest beds present at Clarkston Mountain (Loc. 8) might have wedged- or lapped-out against the eastern side of the Cordilleran geosyncline; because the same faunal units are found near the base of the formation on both east and west it is concluded that the difference must be attributed to a greater rate of deposition nearer the center of the trough. This is further substantiated by the increased spread between faunal zones in the western sections.

In the Swan Peak formation there is evidence for a marked change in these conditions early in Chazyan time, a change leading to the deposition of dark shales, shaly sandstone, and finally clean, white quartzites. Limestone lenses within the shales of the more easterly sections indicate that there were occasional relapses to the Garden City type of sedimentation and that the change was probably gradational to some extent.

Of great interest is the fact that the Swan Peak beds thin and disappear to the southeast within the Logan quadrangle with the shales persisting furthest to the east. The formation may have existed as a uniform sheet over the entire area at one time; since there is an unconformity representing all the rest of Middle Ordovician time between it and the Richmondian Fish Haven dolomite, it is conceivable that the southeast portion of the region may have been broadly upwarped and the Swan Peak beds bevelled by erosion to leave a northwestward thickening wedge. An alternate hypothesis calls for a northwesterly source of the sediments with the shales and a few of the sands being swept as far to the southeast as Blacksmith Fork (Loc. 12), but with the bulk of the coarser arenites being deposited closer to the source.

If the second of these hypotheses is correct, one could expect to find each of the faunal zones progressively higher relative to the Garden City-Swan Peak formational boundary in a northwesterly direction. The answer can undoubtedly be found in the Pogonip limestone and Eureka quartzite in western Utah and Nevada.

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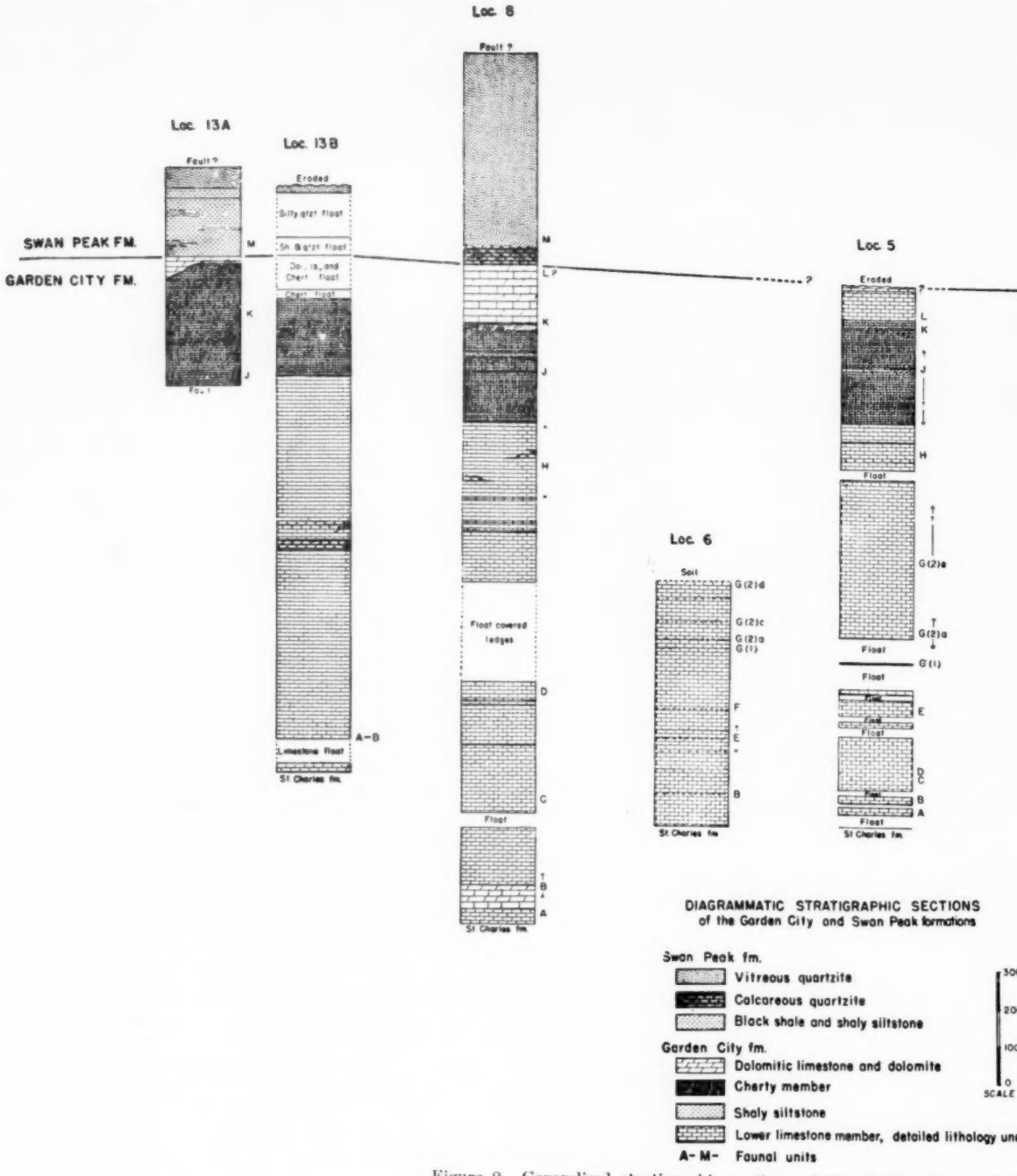
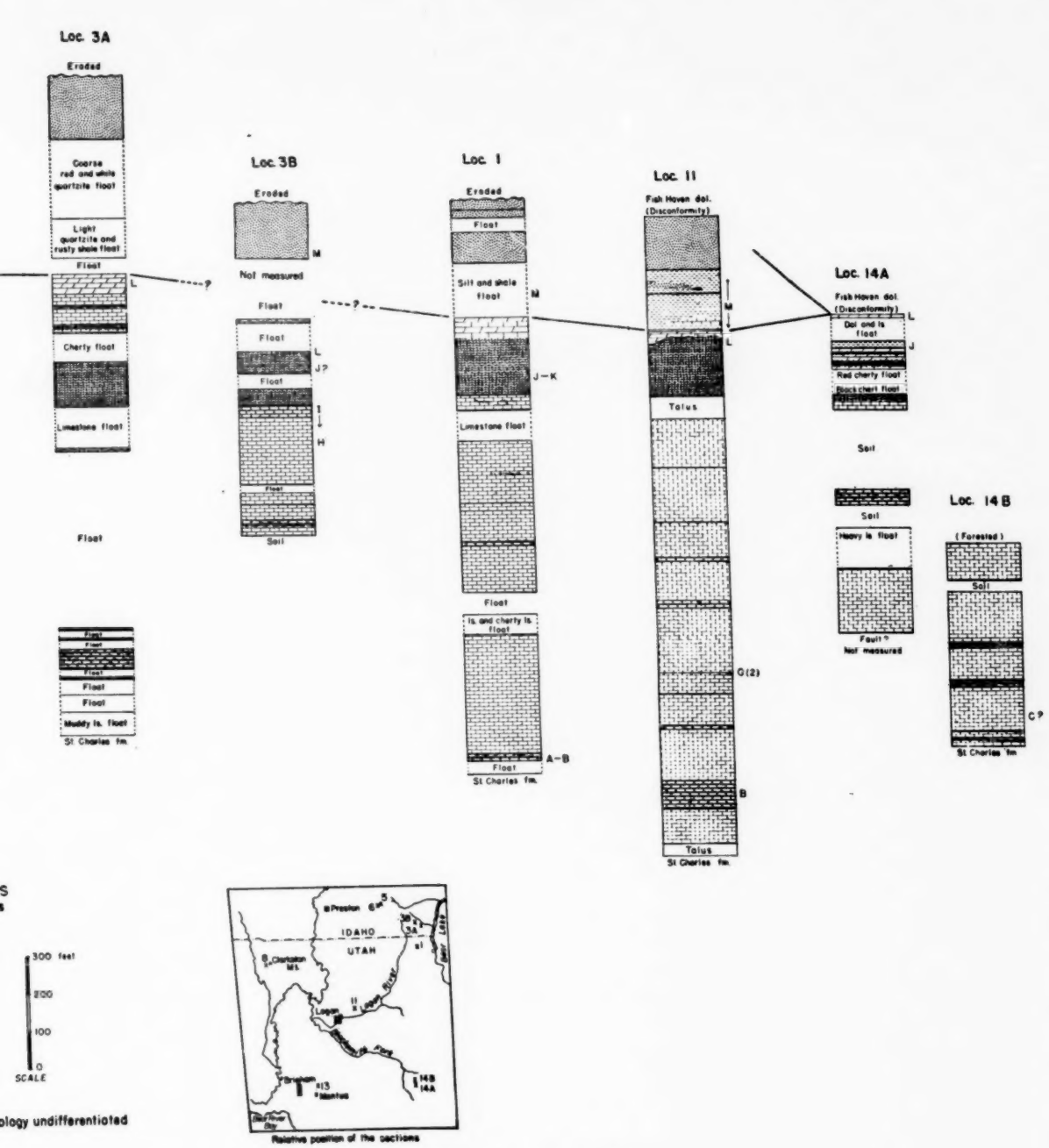


Figure 2. Generalized stratigraphic sections of the Gärden City and S
tween dolomite and top of cherty beds in sections 13A and 11 is gradation



and Swan Peak formations. Refer to figure 1 for locations. Note contact be-
adational, not unconformable.

GROWTH PATTERNS IN THE CERATOPSIA

RICHARD SWANN LULL AND STEPHEN WOOD GRAY

ABSTRACT. The deformed coördinate system of D'Arcy Thompson is applied to both ontogenetic and phylogenetic series of ceratopsian dinosaurs. The results confirm the phylogeny of Lull, 1933, and the relative growth studies of Gray, 1946. An evaluation of the method and its relation to the relative growth formula is provided.

SIR D'Arcy Thompson in his book *On Growth and Form* showed, that, as a one to one relationship exists between homologous parts of the bodies of related animals, this relationship could be expressed in terms of a system of coördinate lines undergoing successive deformation. He suggested that this interpretation of relationship might provide a method for predicting unknown intermediate stages in the evolution of animal groups. He, himself, applied such a system to the phylogeny of the horse, comparing the actually known stages with those derived by deformed coördinates from beginning (*Hyracotherium*) and end (*Equus*) forms only. The agreement was very good. Colbert, 1935, used the method to show form changes but did not attempt to construct a phylogenetic system. Richards and Riley, 1937, used a modification of the method to show the differences between normal and abnormal growth in amphibian larvae. The method has been discussed in general by Woodger, 1945.

THE CERATOPSIA

The present study attempts to apply the deformed coördinate method to the phylogeny of the ceratopsian dinosaurs, a group of ornithischian reptiles from the Cretaceous. Growth of this group was previously studied by means of Huxley's relative growth equation by Gray, 1946, and it therefore seemed to be good material for testing the usefulness of the Thompsonian coördinates.

The specimens used were the series of skulls figured in Hatcher, Marsh, and Lull, 1907, and Lull, 1933. A few other sources supplied single specimens. Enlarged drawings were made from photographs, and coördinate lines were drawn directly upon them. The base grid was chosen arbitrarily for convenience although an attempt was made to have the evenly spaced lines cross as many definite landmarks as possible. Neither brow nor nasal horns were considered in the system as they are too frequently broken or distorted.

The first base selected was the Asiatic *Protoceratops andrewsi* described by Brown and Schlaikjer, 1942, because

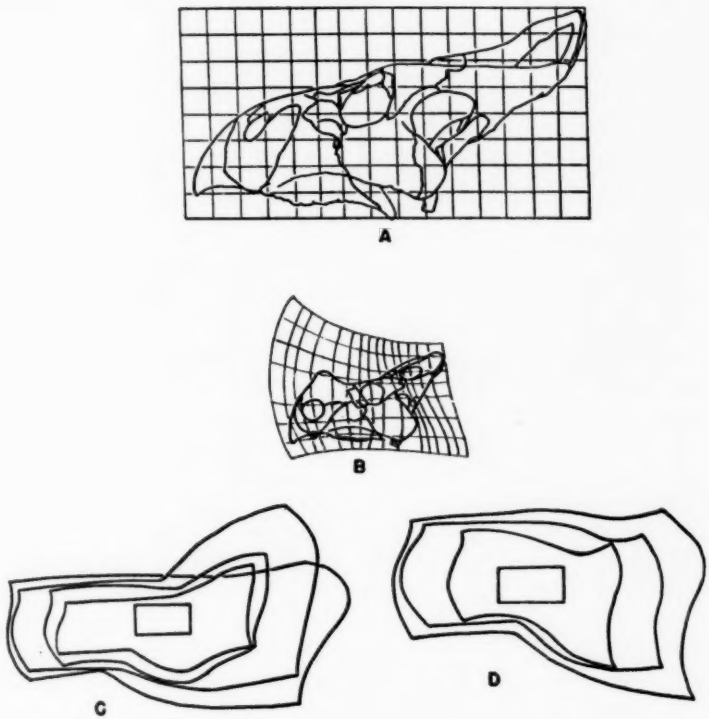


Figure 1. A. *Protoceratops andrewsi* with the basic rectilinear coördinate system. B. Same coördinate system deformed to fit *Leptoceratops cerorhynchus*. C. Same coördinate system (outlines only) for *P. andrewsi* (innermost), *Chasmosaurus belli, C. brevirostris, Pentaceratops sternbergii* and *Torosaurus gladius* (outermost). D. Same coördinate system (outlines only) for *P. andrewsi* (innermost), *Monoclonius flexus, Triceratops prorsus,* and *T. horridus* (outermost).

of its small size, moderate crest development and absence of horns (fig. 1A). Previous studies of the ceratopsian material, Gray, 1946, had shown that there was a discontinuity between the relative dimensions of *Protoceratops* and those of the remainder of the group (fig. 1). This discontinuity resolved itself into a nearly constant deformation of the rectilinear coördinates in all of the higher forms when *Protoceratops*

was used as a base. There is a downward displacement of the post-orbital region superficially apparent from the consistently inferior location of the temporal opening. This displacement is more marked in the ventral than in the dorsal contour lines.

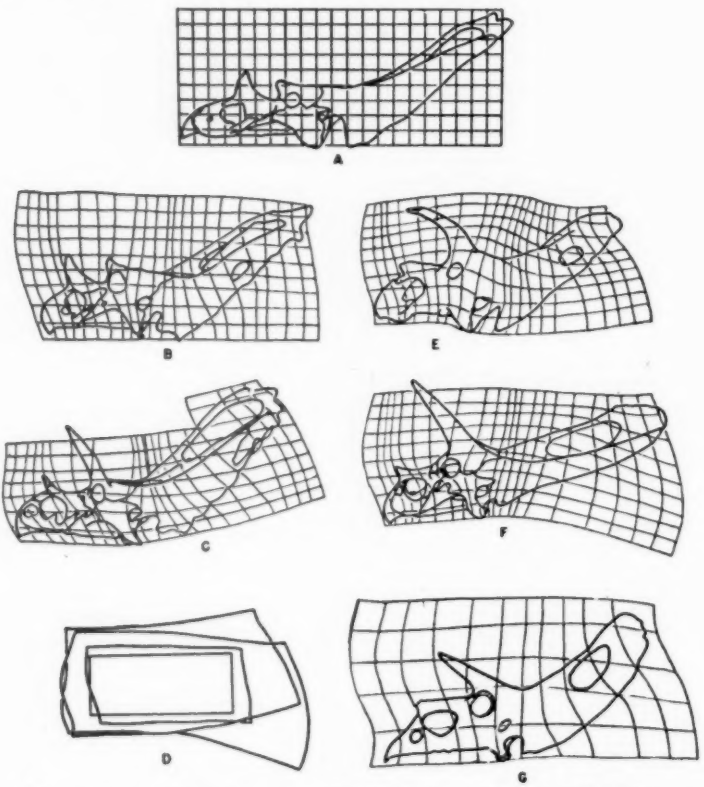


Figure 2. A. *Chasmosaurus belli* with basic rectilinear coördinate system. B. Same system deformed to fit *C. brevirostris*, C. *P. sternbergii*, D. Superimposed outlines of A, B, C, E and F, E. *Arrhinoceratops brachyops*, F. *Torosaurus gladius*, G. *T. latus*.

While it is slightly more prominent in the *Monoclonius-Triceratops* series (the "short-crested" line of Lull) it is present in all of the forms examined, showing neither a constant increase nor decrease as one goes up the series (figs. 1C and D). It is, however, a smooth deformation and *may be drawn with unbroken lines.*

Leptoceratops cerorhynchus (AM 5464), as reconstructed

by Brown and Schlaikjer, does not show any trace of this deformation found in the higher forms but instead shows a quite different pattern of its own (fig. 1B). The extent of reconstruction renders judgment difficult but it does not seem to lie between *Protoceratops* and the other Ceratopsia.

This constant deformation of the Ceratopsia with respect to the base, *Protoceratops*, obscures other changes which may have taken place. New series were therefore constructed. For the "long-crested" line of Lull, *Chasmosaurus belli* (AMNH 5402) was selected as the base form (fig. 2). This skull, from the Belly River formation of the upper Cretaceous has been considered the earliest member of the series culminating in the giant *Torosaurus* of the Lance formation. The only marked deformation in the series is in the angle which the crest makes with the rest of the skull. Both *T. gladius* and *T. latus* from Yale show considerable downward bending of the crest but it should be noted that the skull from the Hell Creek formation of South Dakota assigned to *T. latus* by Colbert, 1947, shows no such deformation with respect to *Chasmosaurus belli* (fig. 2G). It is probable that the crest was easily distorted during preservation and not impossible that its angle with the remainder of the skull was somewhat variable from one individual to another during life. Neglecting this angular deformation of the crest, the phylogenetic growth in the *Chasmosaurus-Torosaurus* line, is very nearly uniform, with a slightly accelerated increase in the posterior lateral edges of the crest.

Arrhinoceratops brachyops (*ROM* 5135), placed doubtfully between the long- and short-crested lines by Lull, 1933, has been shown to belong to the long-crested series on the basis of relative dimensions and the deformed coördinates confirm this conclusion. The deformation with respect to *Chasmosaurus* indicates that, while it is closer to this line than to the *Monoclonius-Triceratops* series, it shows a certain downward bending in the post-orbital region which is reminiscent of that seen in all of the forms when deformed to the *Protoceratops* base.

In the short-crested line, *Monoclonius flexus* (YPM 2015) provided the base for the coordinate system (fig. 3). In general, even less distortion appeared than in the *Chasmosaurus-Torosaurus* series. There was, however, much more trace of the deformation seen with respect to *Protoceratops*. In other words, the downward bending of the post-orbital region noted

between *P. andrewsi* and *M. flexus* was still continuing in the higher forms although to a much smaller extent.

Both this study and the previous one with relative growth seem to indicate that no better classification of the group can be made than that of Lull in 1933.

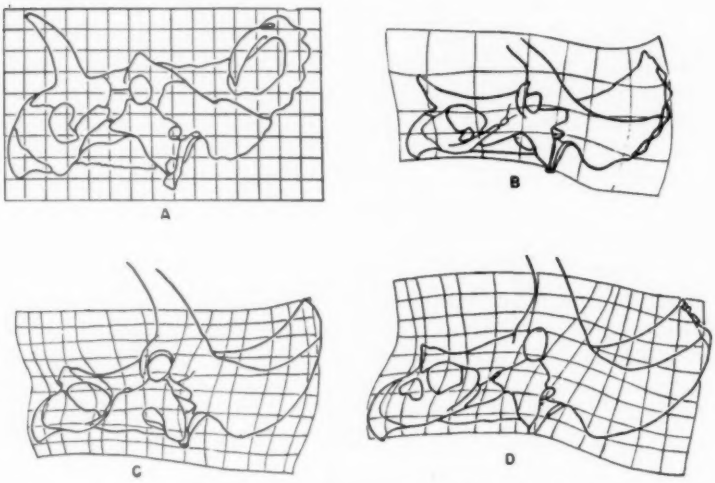


Figure 3. A. *Monoclonius flexus* with basic coördinate system. B. same system deformed to fit *Triceratops prorsus*, C. *T. elatus*, D. *T. calicornis*.

An attempt was made to follow the deformation of both phyletic lines backward in time by extrapolation from *T. prorsus* through *M. flexus* (fig. 4A). It was found impossible to continue the change at the same rate to a point as far "below" *M. flexus* as *T. prorsus* is "above" it. Before reaching such a stage, parts of the deformation become geometrically impossible, that is, the figure begins to buckle and fold. It is possible to reach a stage about three quarters of the way and this is shown in fig. 4A. This completely hypothetical skull shows some resemblance to *Protoceratops* in its small crest and high nasal region, but the position of the temporal opening in relation to the orbit is like that in the higher forms. This character shows no sign of approaching the protoceratopsian condition.

The similar extrapolation from *Pentaceratops sternbergii* through *Chasmosaurus belli* does not at all resemble either of the protoceratopsian skulls. It, in fact, looks like nothing more than a smaller specimen of *Chasmosaurus*. There is no trace

of a tendency to approach *Protoceratops* in the long-crested line.

Changes in the ontogenetic series of skulls of *Protoceratops andrewsi* from Brown and Schlaikjer, 1940, were examined

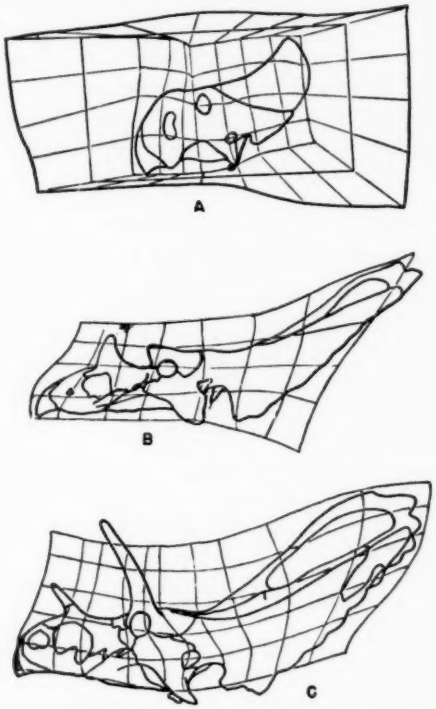


Figure 4. A. Hypothetical skull resulting from extrapolating coördinate system based on *Monoclonius* from *T. prorsus* (outermost) through *M. flexus* backward in phylogenetic time (see Text). B. coördinate system based on *M. flexus* deformed to fit *C. belli*. C. coördinate system based on *T. prorsus* deformed to fit *P. sternbergii*.

from a series of deformed coördinates based upon the youngest specimen (AM 6419) (fig. 5). A series of five skulls shows an excellent set of progressive deformation culminating in the "Old Male" (AM 6432). The greatest change is in the great increase in the depth of the nasal region with age. This is not similar to the condition in the higher Ceratopsia where the nasal region remains relatively undisturbed, all of the growth being localized in an actual horn instead of the more diffuse involvement of the surrounding bone.

In no way does the development of the young *Protoceratops* resemble the phylogenetic changes of the sub-order as a whole. There is no tendency for the temporal opening to shift toward the position found in the higher forms and the increase in the size of the crest hardly forecasts the great crests of the future. The specimens tentatively called females by Brown and Schlaikjer proved to fit the deformation at all points but the nasal region. There is no doubt that these skulls are slightly but consistently different from the other five and this difference may well represent sexual dimorphism (fig. 5A).

DISCUSSION

The Thompsonian grid, being constructed so that lines pass through homologous points in a series of skulls, it follows that

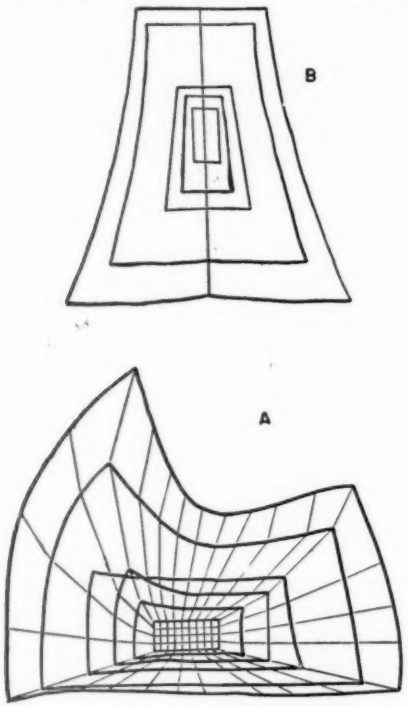


Figure 5. A. Ontogenetic series of outlines of successive deformations of coördinate system taking place in the growth of *Protoceratops andrewsi*. The grid is based on the youngest specimen (AM 6419). The fourth outline from the inside is that of a putative female. B. Similar outlines for dorsal aspect of skull of *P. andrewsi*.

the distance between two points of intersection on one skull is homologous with the distance between the equivalent two points on another skull in the same series. It has been shown in a previous paper (Gray, 1946) that many dimensions on the ceratopsian skulls follow the Huxley equation $y = bx^K$ in both phylogeny and ontogeny. It should follow from this that any pair of line segments in the Thompsonian grid will be similarly related to the homologous pairs of line segments of the same grid distorted to pass through homologous points of another skull of the series. If this "distortion" is simple, uniform growth without bending, and the line segments remain straight, the resulting patterns are capable of ready analysis. If the growth rate in all directions be equal, and the initial dimensions be equal, then b in the Huxley formula equals 1.0 and K equals 1.0. The resulting Thompsonian series will have straight lines connecting all equivalent points of the series (fig. 6D). If b remains equal to one and K becomes greater than one the midpoints of the line segments alone will lie in a straight line and the remaining equivalent points will fall on logarithmic curves concave toward the segment chosen as x. Should K become less than unity the curves will become concave toward the segment chosen as y. This expresses the fact that the value of K becomes its reciprocal if the dimensions chosen as x and y are interchanged (fig. 6C and E).

But such simple growth systems as these are not common, and in practice, in the Ceratopsia, one finds that the axes are deformed and that many varying rates of growth are involved so that rarely do the equivalent points lie in a straight line. In addition to this, the skull is not homogeneous and will resist deformation more in one direction than in another and thus the increase in length of a region due to growth may appear, chiefly, at that end least firmly attached to more slowly growing structures. When, in addition to these complications, it is considered that certain growth rates may change during the phylogeny of a group while others remain constant, it is impossible accurately to analyze the deformed series into its factors without a nearly perfect set of specimens. For this reason it has seemed best to treat most of these lines as being straight. Similarly, while it is possible to analyze the patterns of angular change in the direction of a line in the Thompsonian grid, there is insufficient material to be sure that the skull actually obeys such laws as this analysis might indicate.

When progressive deformations are carried far enough there usually appears a point at which further deformation is no longer possible on a plane surface. Simply expressed, the

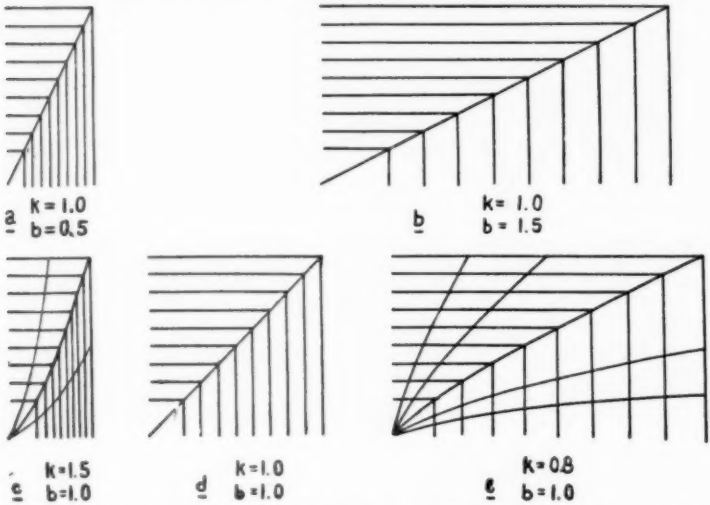


Figure 6. Appearance of quadrants of deformed coördinate systems showing the effects of varying b and k in the Huxley equation.

condition is usually that in which three points form a triangle, one of whose sides grows fast enough to exceed the total of the other two. Such a condition is geometrically impossible and biologically absurd. It was reached during the attempt to extrapolate backward in time in both the *Monoclonius-Triceratops* line and the *Chasmosaurus-Pentaceratops* series. Long before such a condition occurred in nature the forces involved would produce a bending effect upon some one of the structural members involved. An indication that this is already happening in the "Old Male" *Protoceratops* appears in figure 5A. The slow growth of the frontal bones above the orbit with the great increase of the vertical height in the nasal region has produced the elevated nasal prominence. Nevertheless, this growth has placed a strain on the lower portion of the skull so that there is a tendency for it to give in a downward direction and thus produce a more hooked beak. To what extent such rapid growth of one region may affect the history of a group such as the ceratopsia is not clear. They remained well within the bounds of geometrical possibility but had

they not become extinct, and had they continued to increase in size with their same relative skull growth rates they would have reached this interesting stage. As Simpson, 1944, has pointed out, this would affect only the oldest animals first and, even though the resulting stresses might prove fatal, through warping of the upper jaw with resulting mal-occlusion, for example, it would exercise no selective effect until it had progressed far enough to make itself felt in animals of breeding age. Thus, the impending phylogenetic crisis might be first apparent in a decreasing individual life-span.

From these considerations it would appear that there are real limitations to the extent with which orthogenetic or "straight-line" evolution may operate. An increasing dimension need not reach the bizarre and inefficient size necessary to become an impossible burden upon the animal but need only grow to such a point that it can no longer be fitted with other, more slowly growing dimensions. This might well occur in a structure of no great absolute size.

Orthogenesis can operate, then, only within the framework of a Thompsonian grid having line segments of positive sign. Overgrowth of one region may imply that a distant dimension become negative ("folding" or "buckling"), and, while the other side of zero holds no terrors for the mathematician, it is a land closed to dinosaurs.

In summary it may be said that the deformed coördinate system should, under careful analysis, yield, at one stroke, the same information to be obtained from a large series of relative growth measurements. The relationship of ontogeny to phylogeny within such a group as the Ceratopsia may be illustrated both in terms of relative growth of single dimensions and the deformed coördinates in figures 7 and 8. In practice, the required accuracy in the identification of homologous points is not easily achieved and the use of the system is thus markedly limited. It should also serve to indicate probable lines of evolution within the series, and, indeed, will no doubt succeed where more perfect material is available. At present, it seems to be rather less useful, despite the striking nature of its results, than the method of comparing single pairs of measurements which may be available even when the material is fragmentary. With either method it is possible to produce totally spurious relationships; for two points may always be connected by a straight line although evolution may have pro-

ceeded quite differently. Thus, there is a perfectly possible transformation between *Protoceratops* and *Monoclonius* which may or may not be the actual change which took place. There

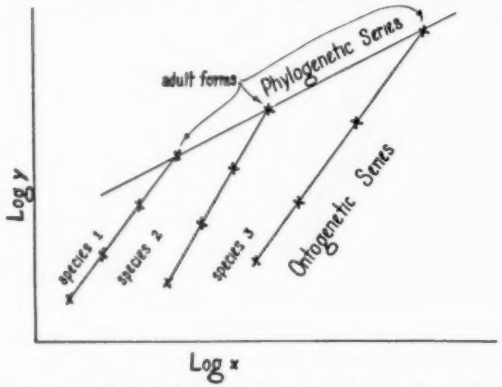


Figure 7. Generalized relation between ontogenetic and phylogenetic relative growth. Where two dimensions, x and y, are compared, each species has its own growth curve with values of b and k peculiar to it. The phylogenetic curve of the *adult* forms intersects each ontogenetic curve with independent values for the variables.

is a deformation of coördinates based upon *Monoclonius* and applied to *Torosaurus* which represents a change which did not occur at all, yet, in neither case would the data alone give one the clue to this. Both methods tell us only that in the case

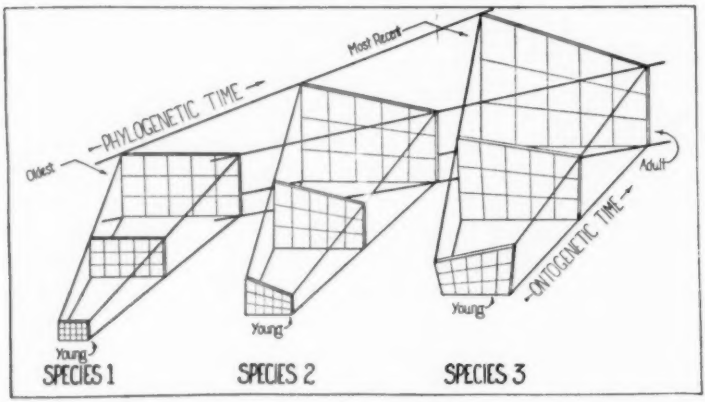


Figure 8. Generalized relation between deformed coördinate systems for three species. As in Figure 7, each ontogenetic series culminates in an adult form which falls into line with other adult forms to create the phylogenetic series.

of two different forms there are certain differences and, *if* the forms are related, it is in a certain way. In spite of these drawbacks, the analysis of the Ceratopsia confirms the relationship previously suggested and further emphasizes the great gap between the Protoceratopsidae and the Ceratopsidae.

Even a casual glance at the deformations produced by this method shows that boundaries between bony elements of the skull are in no sense boundaries of growing systems. The crest behaves as a unit without reference to the boundary between the parietals and squamosals. The orbital region is not the result of a ring of bones growing at different rates but acts as if the whole region were under a single control. Even such units as the crest and the orbital region are so smoothly integrated with one another that one feels that the true "field" can be no less than the entire skull. It is possible that this integration can be broken down into growth centers of some sort, each under some overall control by the entire animal.

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OBITUARY

DR. MAX BLANCKENHORN (1861-1947)

MAX LUDWIG PAUL BLANCKENHORN, pioneer German geologist whose contributions to the advancement of African and European geology are notable, died at his home in Marburg an der Lahn, Germany, in January 1947.

He was born on April 16, 1861, in Siegen where he had his education and was graduated in 1884. He was attracted to the Middle East by reading the scriptures, so that when he went to study further in Strassbourg, he developed his idea of working out the whole African geology. In 1887 he went to Berlin and carried out research work under Professors von Richthofen, Kiepert, and von Bezold. In 1888 he travelled with von Luschon and then alone to Syria and the Euphrates. He received his Doctorate Degree in 1891, his thesis being "Geology of Africa." In 1894, he travelled to Palestine, Sinai and Egypt, and in 1897 he was appointed as a field geologist and later as a paleontologist in the survey of Egypt on the strength of Zittel's recommendation. He mapped large parts of Egypt, travelled the whole of the Middle East, and contributed to the geology and paleontology of that area. In 1898 he became acquainted with Schweinfurth (1836-1925), an acquaintance which later developed into great friendship. They corresponded with each other until Schweinfurth's death, a correspondence which is partly deposited in the *Geologen Archiv*. Blanckenhorn then accompanied Stromer von Reichenbach on his famous expedition to Egypt collecting vertebrate remains, and in 1906 he was in Egypt for the last time as a member of the Royal Prussian Academy of Science expedition for the study of the Nile.

Blanckenhorn represents the last of a generation of geologists whose devotion to work has made possible our knowledge of the geology of areas of the earth where travelling was a difficult, dangerous and annoying task. It needed giant and adventurous figures to cross unmapped and unknown regions of the inhospitable and barren Sahara by primitive means of travel and inadequate, if any, instruments for contacting the outside world.

The period of Blanckenhorn's travels was one of his most prolific and fertile periods. He published more than forty papers on this region. Blanckenhorn's ideas on the tectonics, structure, stratigraphy and paleontology of the Tertiary and Quaternary are still valuable. Many of his terms have leaked into the geological literature of that area. He later condensed his ideas in two books which appeared in the series "Handbuch der regionalen Geologie," namely, "Syrien, Arabien und Mesopotamien" (1914), and "Aegypten" (1921), published in Heidelberg. These two books still remain among the

best written books on that area. At the end of this note a selected bibliography of Blanckenhorn's most important works is given.

Blanckenhorn became later an expert and co-worker of the "Preussischen Landesanstalt" where he examined and published the maps of the region between Kassel and Vogelsberg, and his experience has amplified our knowledge of the vulcanicity and tectonics of that region.

Blanckenhorn suffered during the two world wars. In the last war he lost most of his large library and was impoverished in the post war period. The present writer, an Egyptian geologist, was fortunate enough to be able to acquire the remains of his library and his personal geological instruments which will ultimately find their way to the Geological Museum of the Fouad I University, Cairo, Egypt.

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REVIEWS

The Chemistry and Technology of Enzymes; by HENRY TAUBER. Pp. viii, 550. New York, 1949 (John Wiley and Sons, Inc., $7.50). This book has been written to replace the Author's "Enzyme Technology." It combines in one volume both the industrial and the theoretical aspects of enzymes; thus meeting a need suggested by reviewers of the earlier volume. The first Part of the volume deals with the chemistry of enzymes in considerable detail (15 Chapters, 260 pages) with discussions of preparation, quantitative determination, and properties of them. The second part, on technology (17 Chapters, 259 pages) contains what appears to be a most up-to-date treatment of the industrial use of enzymes in the fermentation, baking and other food industries, medicinal, textile, leather, and other industries. The book reads well, has clear illustrations and appears to be thoroughly documented. The type and format give the book a good appearance. HAROLD G. CASSIDY

Dynamic Aspects of Biochemistry, American Edition; by ERNEST BALDWIN. Pp. xviii, 457. New York, 1947 (The Macmillan Com-

pany, $4.00. As the Author points out, biochemistry of necessity started from investigation of the chemical structure and configurations of the organic building blocks of living matter. This might be called the morphological aspect of the subject, and is being continually advanced. Built upon this foundation, and of increasing importance and sublety are the investigations of the functions of these building blocks. This is the dynamical aspect of biochemistry. The volume is divided into two Parts: I, Enzymes, and II, Metabolism. The first two chapters of Part I give an excellent summary of the general aspects of enzyme behavior; the remaining three deal with specific groups of enzymes. The second Part contains a thoroughgoing discussion of the methods used in investigating intermediary metabolism; of the metabolism of carbohydrates, and of fats. There is a remarkable index of 37 pages in double columns. This book is designed as an advanced text. It should also be most valuable to one who wishes to read in the field. Not only will it refresh his memory and bring him up to date (1946) but it will provide the stimulating and idea provoking experience which those who have enjoyed the Author's "Comparative Biochemistry" (AM. JOUR. SCI. **237**, 365 (1939)) will expect. HAROLD G. CASSIDY

Annual Report on the Progress of Chemistry for 1947 (*Volume* 44); Issued by the Chemical Society. Pp. 327. London 1948 (The Chemical Society, 1). This volume, written by twenty experts summarizes the important advances which have been made in pure chemistry and related subjects up to the end of 1947. This, like its predecessors, is an extremely valuable volume because of its completeness and the general clarity and style which adorn it. The twenty topics are classified under the headings of General and Physical Chemistry; Inorganic Chemistry; Organic Chemistry; Biochemistry; Analytical Chemistry. The reader can thus gain, in a pleasant manner, a comprehensive view of many fields. For example, those interested in the earth sciences might find "The Kinetics of Electrode Processes" by J .N. Agar, which opens the volume, of equal interest with H. J. Dothie's "X-Ray Analysis" which is the penultimate topic. HAROLD G. CASSIDY

Microwaves and Radar Electronics; by ERNEST C. POLLARD and JULIAN M. STURTEVANT. New York, 1948. Pp. vii, 426, 13.11 figs. (John Wiley and Sons, Inc., $5.00).—This book is a survey of microwaves and radar electronics, written for newcomers to the field who want to discover the potentialities of these new techniques. It should be particularly useful to two specific audiences—those who want to know what the microwave field is all about but who do not intend to use this particular volume as a technical manual, and those

who seek a fluent familiarity with the nomenclature but can allow some one else to work out practical details.

The coverage of the book is good. The authors start with two chapters on fundamentals. They require an elementary knowledge of differential and integral calculus and vector notation, but the understanding of these two chapters is not prerequisite to an appreciation of later material. The third and fourth chapters under the titles of "The Production of Microwaves," and "Microwave Technique" give a general discussion of specifically microwave electronics. Chapters 5 to 11, comprising almost half the book, describe the electronic control circuits which have been designed for use with radar systems. These chapters should prove very useful to everyone interested in a summary of the chief advances made in electronic circuits during the war, particularly at the Radiation Laboratory at M.I.T. The description is sufficiently general so that the reader may easily recognize the value of these circuits in applications beyond the radar systems for which they were designed. Two chapters on radar and its accessories and microwave communications give brief explanations of the operational details of representative examples of these subjects.

The last chapter on "Microwaves in Physical Research" was somewhat of a disappointment. A consideration of the kinds of physical processes which might be investigated by the microwave method would have been more valuable than the discussion of specific examples to which the authors have limited themselves. It is obvious in a book on radar techniques that the emphasis should be on pulsed microwaves. The microwave techniques discussed, however, are not restricted to transient phenomena and particularly in physical research, the value of c-w magnetrons and other steady power sources is great. It is unfortunate that this chapter on Physical Research does not point out clearly the possibilities of the steady source techniques as differentiated from the radar electronics.

The use of Radiation Laboratory slang makes the book unnecessarily difficult to read and robs it of considerable dignity. The inclusion of such terms as TR "boxes" for TR switch tubes, "the main bang" for trigger pulses, and "strips" for i-f amplifiers adds nothing to the clarity of presentation. Even an expert in the field may find confusing a quotation such as follows, "FTC and DBB circuits are most effective when used in conjunction with IAGC. The FTC and IAGC combination is effective for jamming by unmodulated c-w or c-w modulated at frequencies below the FTC cut off frequency, while the DBB and IAGC combination is best in cases of noise-modulated jamming and most types of clutter, especially clouds."

This reviewer believes that survey books make their real contribution by serving both as an introduction to the field and as a point

of departure for the reader who needs specific and detailed information for a particular problem. Generally speaking, this book fails in the second objective, since many of the references are too indefinite to be useful. Too many of the footnotes read: "A detailed treatment will be found in the 'Radiation Laboratory Technical Series' published by McGraw-Hill Book Co.". Since there are twenty-seven volumes of this series, such a reference clarifies nothing. Although not all the volumes have yet appeared, the indexes of the unpublished volumes have been available for some years and a little investigation by the authors would have provided much more specific information. About half the references are to Radiation Laboratory Reports, and these are available only to a limited audience. Furthermore, as of January 1949, a check shows that 15% of the cited reports are still classified. It is clear that too little emphasis was placed on a proper selection of references to make them really useful.

SANBORN C. BROWN

Submarine Geology; by FRANCIS P. SHEPARD. Pp. xvi, 348; Bathymetric chart and 106 figs., New York, 1948 (Harper and Brothers, $6.00).—This addition to Harper's Geoscience Series by one of the most productive students of a new branch of geology should stimulate all students of earth science. Professor Shepard has made a valiant effort to dovetail the many related facets of oceanography and geology within a small volume. So rapidly are new techniques being devised and new data gathered, however, that the book is destined to become somewhat obsolete in the very near future, through no fault of the author, by virtue of geophysical advances. He clearly envisages this in a brief mention of equipment for the investigation of submarine geology in the Summary. The book is nonetheless a valuable contribution for all global-minded geologists pointing up as it does the unsolved problems of world-wide significance, solution of which depends on the methods (some yet to be devised) of submarine geology. The publishers have fashioned an attractive volume of high quality and pleasing format. The price seems high inasmuch as only one-third of the figures are halftones, most of them of small size.

The treatment is more that of a monograph than of a textbook, but this is probably inevitable in a field of inquiry so young and fastgrowing that a "standard" work will not be possible for many years. Oceanography was pursued very largely by non-American workers virtually up to World War II. Although he mentions a few such contributions in Chapter I, Shepard leans almost exclusively upon recent American work and freely admits (p. 9) embarrassment at the concentration of references to New England and California, areas in which he has specialized.

As Dr. Carey Croneis remarks in the Editor's Introduction, "some portions of the book may well come to be regarded as iconoclastic." This is due no doubt to Professor Shepard's keen enthusiasm and exuberance. The serious students will be stimulated but not misled by his Now It Can Be Told! style. Topic headings like "Some debunking" and "More debunking" in the discussion of continental shelves illustrate this. The author's enthusiasm occasionally carries him to sweeping generalizations. For example, under Significance of Glaciated Shelves one reads (p. 327) "Virtually all glaciated coasts have a superabundance of deep harbors, whereas harbors have to be constructed, or at least deepened, along most unglaciated coasts." What about, say, Rabaul, Tokyo, Manila, Rio and San Francisco, to say nothing of the great atolls of the Pacific such as Ulithi? In studies of continental shelves, particularly with submarine canyons, the author's experience is unequalled and the book reflects many original contributions.

Some conclusions, however, purporting to reflect results of recent studies by the author, are in fact so old that their origin is obscure. For example, in his summary of Waves, Currents and Engineering Structures (pp. 322-4) Shepard states: "The investigation of waves . . . combined with recent studies of shore processes, particularly along the California coast, may provide a new basis for shore planning . . . . " He then lists sixteen "new discoveries, partly confirmation of principles not well understood previously" the majority of which have been known and utilized along heavily populated beaches of our east coast and in England for generations. The U. S. Beach Erosion Board has operated on these principles for nearly twenty years and before that state organizations like the New Jersey Board of Commerce and Navigation and State Geological Survey turned out detailed reports confirming these well-known principles.

A few errors have crept in, perhaps unavoidable in a new book. The already famous U. S. Hydrographic Office Chart No. 5485, first of a new series, is misnumbered (p. 3) 5495. Figure 96 showing seamounts (guyots) in the western Pacific is credited to H. O. Chart No. 2603 whereas it is actually a copy of Figure 1 in a paper by Hess published in this JOURNAL (Vol. 244, p. 774, 1946). Figure 33, a diagram of beach terminology, is uncredited although it appears identical with Figure 1 of the Interim Report of the U. S. Beach Erosion Board of 15 April 1933.

SUBMARINE GEOLOGY is a welcome addition to geological literature. It briefly poses some of the greatest unsolved problems of geology, such as the origin of continental shelves, submarine canyons, flattopped seamounts and the Mid-Atlantic Ridge, conclusions about which are either scanty or highly controversial.

Chapter bibliographies invite the serious student to original sources of varying opinions. It should be of wide interest to all who know and love the sea and its shores, particularly to geologists and geophysicists engaged in its study and exploration. JOHN B. LUCKE

Foraminifera: Their Classification and Economic Use, with an Illustrated Key to the Genera; by JOSEPH A. CUSHMAN. Fourth edition, revised and enlarged. Pp. 605, 9 figs., 55 pls., Cambridge, Massachusetts, 1948 (Harvard University Press, $10.00).—The appearance of the fourth edition of this outstanding work marks its twentieth year of invaluable service to students of Foraminifera. The first ten chapters of the text, covering the general aspects of the subject, are preserved without appreciable change from the third edition. The remaining systematic portion of the volume is enlarged by the addition of analyses of 129 genera described since the third edition. The geologic range of many of the older genera has been changed in the light of recent work.

In revising the section on fusulines, Carl O. Dunbar has separated the group into two distinct families, the Fusulinidae and the Neoschwagerinidae, thus increasing the total number of families from 49 to 50. The section on the orbitoids by T. Wayland Vaughan and J. Storrs Cole has been revised by Cole.

Seven new plates are added to the key to accommodate the illustrations of the additional genera. These illustrations maintain the high standards set in preceding editions. The bibliography has grown appreciably and includes a new section on Foraminifera as related to oceanography.

In continuing the use of the name *Camerina* and the family Camerinidae, Cushman seems to have overlooked the fact that under suspension of the *Rules,* the International Commission on Zoological Nomenclature in 1945 (Opinion 192) validated the name *Nummulites* and placed it on the official list of *nomina conservenda.* It should therefore replace *Camerina.*

Foraminifera has long been a standard paleontological reference of great popularity both here and abroad. A volume so well known and so widely acclaimed needs no further praise. Dr. Cushman deserves the thanks of all students of Foraminifera for his efforts in keeping this excellent work up-to-date. KARL M. WAAGE

Bibliography of the Literature on Sodium and Iodine in relation to Plant and Animal Nutrition. Pp. 123. New York, 1948 (Chilean Nitrate Educational Bureau). This compilation of abstracts, primarily from Chemical Abstracts, on the literature of sodium and iodine in relation to nutrition is part of the more extensive collection of abstracts on the minor elements. It is a useful guide to

the literature on the occurrence and physiological action of sodium and iodine. The index, however, is misleading since some elements are mentioned even if they merely are used as reagents in some analytical procedure. EVA M. LOW

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